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Overview of Principles and Rules of Geometrical Product Specifications According to the Current ISO Standards

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The article provides an overview of the philosophy of geometrical product specifications (GPS), which are, in addition to material specifications, a key component of effective planning and production of mechanical products as well as communication between partners in these processes. The principles and basic rules for precise and unambiguous specification of all requirements are embodied in a series of ISO GPS standards. It includes standards that describe the required accuracy of geometrical features of size and geometrical tolerances. An overview of the fundamental principles and rules imposed by the current ISO GPS standards and their content was carried out. This includes a description of the organization of the ISO GPS system and a summary of the content of the more relevant standards, which have recently undergone multiple revisions. The ISO GPS standards are based on the duality principle of specification and verification. In the present research, we focused primarily on geometrical specifications, while omitting the parallel pillar of verification, which, according to the ISO GPS matrix model, contains an even greater number of standards that define this area in more detail.
Keywords: ISO standard, geometrical product specification, geometrical dimensioning and tolerancing, principles, rules, size, tolerance, verification

Highlights
- *Overview of the organization of ISO geometrical products specification (GPS) standards and the fundamental principles and rules given in the current editions of these standards.*
- *Specification of the accuracy of linear and angular sizes of geometrical features and other dimensions in technical documentation.*
- *Specification of the accuracy of geometrical features of workpieces.*
- *General tolerances for size and geometry.*
- *Other important ISO GPS standards.*

0 INTRODUCTION

Geometrical product specifications are, in addition to material specifications, a key part of the information necessary for effective design, planning, production, and monitoring of products throughout their lifecycle. This is especially true for mechanical products, namely components or assemblies of various machines and devices. Individual components must display appropriate characteristics of different parts of their geometry, which are primarily surfaces, but also the lines and points on these surfaces, viewed in a three-dimensional (3D) or two-dimensional (2D) space (technical drawings). These basic building blocks are generally referred to as geometrical features. Depending on the purpose and function of components in assemblies, different features play more or less important roles in ensuring that components are assembled into sets and perform their tasks (main tasks and sub-functions).

Mechanical engineers have been managing this issue by setting tolerances, which are defined in various standards and whose values depend on the functional analyses of the roles of individual components and assemblies in the common function of a machine or device. These tolerances need to be determined and specified in the technical documentation of individual components (traditionally in workshop drawings).

In the present day, the process of developing and planning mechanical products is shifting towards specifying all geometrical requirements already in the phase of virtual 3D modelling of products; model based definitions (MBD). Logically, all necessary specifications (tolerances) regarding permissible deviations from the theoretically exact geometry (TEG), as specified in virtual models, are added to the virtual models at this stage. Since this information is non-geometrical or geometrically and visually hard to detect, a system of principles, rules and symbols is needed that can record such information easily and, above all, completely unambiguously either in 3D product models (adding appropriate attributes such as comments and symbols) and/or, at a later stage, in technical product drawings (primarily 2D workshop drawings).

Globally, two standard systems have been established in this area for practical use:
- ASME standards (ASME Y14.5 and others),
- ISO system of standards for the area of geometrical product specifications (GPS).

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Over the past 20 years, the ISO GPS system has been adopted as a set of national standards by most European countries as well as by many other countries and associations. During this period, many new standards have been created, many have been updated, and the dynamics of updating continues in line with the development of manufacturing technologies as well as quality control technologies (verification – measurement).

This paper will briefly describe the current state of the ISO standards system for GPS, its starting points, key general principles, and rules. Certain innovations will be described that either break away or significantly differ from previous practices, or else provide clear definitions of previously non-existent principles and rules. One of the main concepts and goals of the GPS standards is the completeness of definitions in technical documentation and complete unambiguity of specifications.

Currently, there are not many book sources available that would systematically and extensively discuss the area and be in line with the current state. Since the dynamics of verification, updating, and adoption of new ISO standards in this field has been relatively high over the past two decades, all sources are quickly becoming obsolete. Nevertheless, the following should be mentioned: [1] to [5] and [6] to [12].

1 ORGANIZATION AND BASIC PRINCIPLES OF ISO GPS STANDARDS

Numerous ISO standards determining the basic principles, rules and symbolic language that concerns the method of technical product specifications are divided into a group of standards relating to technical product documentation (TPD), which is overseen by Technical Committee 10 (ISO/TC 10), and a group of standards on GPS, which is overseen by Technical Committee 213 (ISO/TC 213). The TPD group comprises a set of standards that lay down the basics of displaying technical products in various technical drawings: principles and rules for displaying products in 2D projections of spatial objects, technical fonts, carriers of technical drawings, equipment for making drawings, etc.

The group of GPS standards is extensive and sets out principles and rules for recording geometrical product specifications that are not merely visual and therefore require an agreed and coordinated symbolic language. According to ISO terminology, this symbolic language helps to prepare clearer and more understandable descriptions of various operations used to compose different operators. In practice, this means clear and unambiguously defined sequences of procedures (operations can simply be called recipes) which lead to clear and complete specifications of geometrical requirements for selected geometrical features (explicit requirements) or generally for all features that are not explicitly marked. A similar statement, but possibly with different operators, can be applied to the other fundamental pillar of GPS, i.e. verification [1], [5], [13] and [14]. Every specification of geometrical requirements inevitably leads to appropriate verification, and ISO GPS unambiguously links this according to the principle of duality.

Most of our review content consists of chapters and standards from the narrower area of GPS, called in the American Society of Mechanical Engineers (ASME) geometrical dimensioning and tolerancing (GD&T). The content can be divided into the following summarized points that apply to the geometrical features that make up a workpiece:

- basic principles and rules of GPS;
- features of (linear and angular) size and distance and orientation dimensions (linear and angular) and their tolerances;
- specifications of geometrical tolerances (GT) that are independent of other features of the product:
    - form GTs of lines and surfaces;
- specifications of GTs that depend on other product features (require definitions of references, i.e., datums):
    - orientation GTs of lines and surfaces,
    - location GTs of points, lines and surfaces,
    - runout GTs of lines and surfaces;
- datums (references necessary for the specification of orientation, location, and runout of GTs);
- surface conditions that are visually hard to recognize and are limited by way of permissible:
    - roughness,
    - waviness,
    - primary profile (sum), and
    - specified limitations of local surface defects;
- specifications regarding the allowed conditions of theoretical sharp edges, which are the mathematical boundaries between surfaces.

All GTs are divided into two classes according to the basic definitions of tolerance zone type and shape:

- line GT and 2D tolerance zones, and
- surface GT and 3D tolerance zones.

According to the ISO philosophy, the geometrical features to which geometrical tolerances can be applied and which also affect the correct interpretation of the specification and the appropriate product verification operations are divided into:

- **integral** features, which are individual features that can be physically touched by measuring means during the verification process (individual external surfaces, lines or points);
- **derived** features, which cannot be directly touched, but are mathematically determined from adjacent symmetrical integral features (median or statistically median points, lines, and surfaces).

Features of size (FoS) hold a special status in GPS, in particular as regards the specification and verification of GTs. The definition includes external surfaces (shafts) and internal surfaces (holes), all with their associated characteristic dimensions (e.g., diameter, distance between two parallel surfaces) and the size tolerances of the measured dimensions. In assembling workpieces with such characteristics, various fits (clearance, interference and transition) are formed, which are key to determining the possibility of assembly and functional properties of assemblies. To ensure the appropriate precision of the orientation and location of these FoS's which crucially affect the possibility of assembly and functioning, the corresponding geometrical tolerances are typically specified. However, these tolerances are usually not applied to integral features, but to derived features (axes or median planes) of such FoS. This approach enables the use of additional "material" requirements; maximum material requirement (MMR), least material requirement (LMR), reciprocity requirement (RPR), which also allows systematic use of classic mechanical fixed gauges, (MMR), known in many industrial environments and languages as "calibres", or at least virtual fixed gauges, (LMR).

All definitions of geometrical tolerances in ISO standards are by default based on the principle that during verification each extracted point of a feature (integral feature) or each mathematically derived point (derived feature) must be within the defined tolerance zone (either 2D or 3D). In practice, this is commonly known as the "classical" definition of tolerances, or "the worst-case tolerance". With new or additional indications for geometrical tolerances, the specification can be modified in such a manner that the entire mathematically defined feature (i.e., associated feature), which is determined by appropriate operations (e.g., mathematically ideal surface envelope at the maximum or minimum material amount, Gaussian or Chebyshev (minimax) associated line or surface, etc.), must be within the tolerance zone. We arrive at such a feature by using appropriate operations on the cloud of extracted points on the real surface of the product (operations: extraction, filtration, association, collection, construction).

By stating an appropriate explicit requirement in the documentation, every dimensional and geometrical tolerance can also be defined as a statistical tolerance. This part is not addressed in the ISO GPS standards. In principle, this means that only a certain percentage of extracted or derived feature points determined as a result measurements during verification must be within the tolerance zone. In practice, it turns out that the use of statistical tolerances and tolerance analyses is still not as common and widespread as anticipated and possible [12].

1.1 Organization of ISO GPS Standards

ISO standards for geometrical product specifications are organized into a matrix [13] which roughly presents their content and purpose. The standards are divided into three main groups:

1. Fundamental standards: determine common starting points, default principles, and rules;
2. General standards: essential for practical engineering use, contain special rules and symbolic language;
3. Complementary standards: important other standards for comprehensive geometry management (e.g., standards on machine elements).

Global standards (the category has been removed from ISO 14638:2015 edition [13]): a former category that contained definitions, concepts and terminology that were not necessary for everyday practical engineering work (but certainly for the management, organization, software solution programmers, etc.). Standards which were formerly classified as global GPS standards have either been withdrawn or can be categorized as fundamental or general GPS standards.

Additionally, certain documents lie outside the scope of the ISO GPS system but are necessary for verification (e.g., International System of Units (SI units), International vocabulary of metrology (VIM), Guide to the expression of uncertainty in measurement (GUM).

The GPS matrix system was first defined in 1995 and revised in ISO 14638:2015 [13]. It is classified among the fundamental standards and is important for understanding the entire system. Another key fundamental standard is ISO 8015:2011 [14], which was thoroughly revised and supplemented in this last revision and provides key concepts, principles, and rules for correctly understanding and using GPS standards. In brief, the most important principles can be summarized in the following points:

- Invocation principle; if one part of the ISO GPS system is explicitly used in a drawing, the entire ISO GPS system applies.
- Hierarchy principle; according to this principle, rules in a standard at a higher hierarchy level (fundamental, global, general, complementary) apply unless a standard at a lower level explicitly gives a different rule.
- Definitive drawing principle; all requirements must be indicated on the drawing, in the documentation referenced on the drawing or in the contract, and it cannot be expected that requirements that are not indicated will be fulfilled.
- Feature principle; the component consists of features with natural (mathematical) boundaries and – unless otherwise specified – each GPS specification applies to the entire indicated feature and only to this one feature.
- Independency principle; unless otherwise specified, each GPS specification for a feature or a relation between features must be fulfilled independently of all other requirements in the specification. This is an important principle compared to some other standards (previous and existing), which by default have a certain connection (dependency) between different specifications (e.g., Rule #1 in ASME Y14.5 – the envelope rule).
- Decimal principle; in GPS all numbers are considered exact (trailing and leading zeroes of non-specified decimal numbers).
- Default principle; a default rule is a rule that applies when nothing else is specified.
- Reference condition principle; defines the conditions under which the GPS specifications apply to the component (reference temperature defined, clean workpiece, etc.).
- Rigid workpiece principle; all specifications apply to the component in the free state, i.e., without influence from external forces including the force of gravity.
- Functional control principle; GPS is based on the idea that the function of a component only depends on the material properties and the geometrical properties of the component.
- General specification principle; general tolerances only apply to characteristics for which there is no individual (explicit) specification. An individual specification can be more or less restrictive than the general tolerance.
- Responsibility principle; in GPS, specifications and verifications are not considered as either completely correct or completely wrong. Instead, they are evaluated on their level of uncertainty and/or ambiguity (Correlation and Specification ambiguity and Measurement uncertainty).

Decision rules for verifying conformity or nonconformity with specifications are very important and are stated in a multi-part standard ISO 14235 [15] and [16], especially in 1st part, 2017 edition. These rules distribute the combination of the specification ambiguity, which is the responsibility of the designer, and the measurement uncertainty, which is the responsibility of the party proving conformance or non-conformance. The relevant principle is discussed in the paper in next Subclause 1.2.

1.2 Duality Principle in ISO GPS Standards

The principle of duality is one of the most important principles and states that each geometrical specification (basic pillar) is followed by an appropriate verification (parallel pillar). We determine the specification using appropriate specification operators, which shall sequentially clearly and unambiguously lead to the definition of the geometrical characteristic. Specifications can be composed of the following operations [2], [5] and [58]:

- **Partition** separates the feature(s) involved in the specification;
- **Extraction** defines a set of points that is the digital representation of a feature;
- **Filtration** suppresses certain wavelengths in the surface;
- **Association** defines an ideal feature (without form error) from a set of extracted points on surface of real part (with form error);
- **Collection** considers a number of features as one entity;
- **Construction** defines new ideal features from two or more ideal single features;
- **Evaluation** defines a numeric value from one or more features. The evaluation is always the last operation in a recipe.

Each product can be represented using different types of product spatial virtual models, on which the necessary operations for specification can also be determined and observed:

- **Nominal** model: a mathematically geometrically ideal CAD model of product surfaces without any defects or deviations, indicating geometrical specifications;
- **Skin** model: a surface model of a product that includes possible geometrical and dimensional deviations;
- **Real** model: a model that represents surfaces using clouds of extracted (measured) points on the surfaces (integral features) of the real product.

Verification is also defined using an appropriate operator composed of a correct sequence of verification operations. It is therefore necessary to take into account correlation and specification ambiguity, as well as measurement uncertainty which is inevitable and must be appropriately determined or estimated based on the measuring devices and procedures used. This means that due to measurement equipment limitations, methods and procedures, verification does not necessarily follow the operations given in the specifications. However, it is necessary to correctly consider measurement uncertainty when evaluating the result.

Table 1. *ISO GPS standards matrix* [13] *(simplified example for ISO 1101)*

	Chain Links						
	A	B	C	D	E	F	G
Size							
Distance							
Form	•	•	•				
Orientation	•	•	•				
Location	•	•	•				
Run-out	•	•	•				
Profile surface texture							
Areal surface texture							
Surface imperfections							

specification
A Symbols and indications
B Feature requirements
C Feature properties

verification
D Conformance and nonconformance
E Measurement
F Measurement equipment
G Calibration

Therefore, standards define the specification and verification of a geometrical characteristic as the ordered set of operations. A specification operation is an operation that is formulated using only mathematical or geometrical expressions or algorithms, or both. These are step-by-step and sequential steps that can be defined mathematically and descriptively as a kind of recipe that leads us to the desired result. Individual steps in this recipe are called operations and the ordered set of operations is the operator.

The principle of duality is also taken into account in the matrix of the standard chain, which divides this matrix into two pillars: the specification column and the verification column (Table 1). The matrix is composed using seven chain links (A to G columns) and currently nine geometrical properties in the chain of standards, which ensure clear definitions of the content of GPS standards. Each ISO GPS standard can regulate the content that belongs to one or more chain links from A to G in this matrix, which is clearly marked in all GPS standards.

Most ISO standards from the GPS group (currently about 144) relate to the product verification pillar (measuring equipment and methods, measurement uncertainty, etc.). In this paper, we will limit ourselves to standards governing the specification of geometrical characteristics, [13] to [67], which must be followed by verification. Similarly, we will also omit the broad field of surface property specifications (roughness, waviness, primary profile - ISO 21920:2021 [46] to [48]) and edges (ISO 13715:2017 [49]) and corresponding verifications (several ISO standards).

2 TOLERANCE OF LINEAR AND ANGULAR DIMENSIONS

The old division of specifications used to control the accuracy of dimensions indicated on workshop drawings and the geometrical properties of a product was unrefined and unclear, distinguishing only between

- tolerances of linear and angular dimensions, and
- geometrical tolerances.

There was no clear correlation regarding the purpose of linear dimensions, or whether they represent the FoS or the position or orientation of a feature in space. Furthermore, it was not clearly defined whether an angular dimension could represent a characteristic size of a feature or only its orientation. The rules for defining the geometrical characteristics of features (form, orientation, location) have always been clearer, but still incomplete.

The ISO 14405 standard [17] to [19] belongs to the group of general GPS standards and now clearly defines in three parts the tolerances of linear and angular dimensions, typically representing the size of shafts and holes (Parts 1 and 3; FoS: circle, cylinder, pair of prismatic surfaces, cone, pair of pyramidal surfaces, etc.) and what are other linear and angular dimensions that are not classified as “size”. In the second part, the standard gives recommendations on tolerancing for features associated with these linear and angular dimensions (location and orientation GT – Part 2).

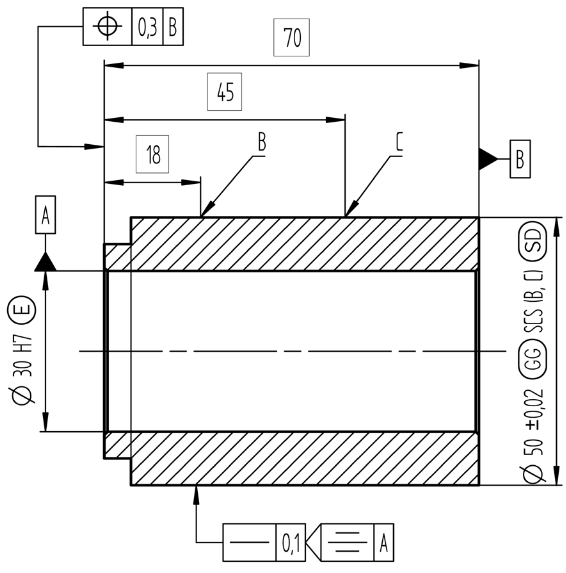
ISO 14405-1:2016 [17] defines the default definition of linear size (Table 2, Fig. 1) and determines various other special specification operators for the linear size of shafts and holes (FoS). The default definition of size is still, as before, any possible distance between two opposing points (LP) on features (surface/s) lying on the same normal, passing through the derived line or plane (axis or median plane).

Table 2. *Linear/angular size specification modifiers*

	Modifier	Linear Sizes [17]
Local linear sizes:	(LP)	Local two-point size (default size)
	(LS)	Local size defined by sphere
Global linear sizes:	(GG)	Least-squares association criterion
	(GX)	Maximum inscribed association criterion
	(LP)	Minimum circumscribed assoc. criterion
	(GC)	Minimax (Chebyshev) association criterion
Calculated linear sizes:	(CC)	Circumference diameter
	(CA)	Area diameter
	(CV)	Volume diameter
	Modifier	Angular Sizes [19]
Local angular sizes:	(LC)	Two-line angular size with minimax association criterion (new default size)
	(LG)	Two-line angular size with least squares association criterion
Global angular sizes:	(GC)	Global angular size with least squares association criterion
	(CC)	Global angular size with minimax association criterion
	Modifier	Statistical linear/angular sizes [17] and [19]
Rank-order sizes:	(SX)	Maximum size
	(SN)	Minimum size
	(SA)	Average size
	(SM)	Median size
	(SD)	Mid-range size
	(SR)	Range of sizes
	(SQ)	Standard deviation of size

However, the standard now fully defines many other possible operators on how to determine the linear size of a feature. These methods (operators) are divided into four groups: local sizes (2), global sizes (4), calculated sizes (3), and statistical sizes (7 rank order linear sizes).

The ISO 14405-3:2016 [19] default specification operator for angular size is the "two-line angular size" with minimax association criterion (Table 2, Fig. 2). The standard determines additional specification modifiers for the angular size of shafts and holes (FoS). The default definition of angular size is now different (see Fig. 4 in ISO 14405-3 [19]) from what it used to be (the angle between two envelope lines in the cross-sectional plane easily measured with mechanical protractors) and is determined by the mathematical "minimax" (Chebyshev) rule, which represents a mathematical definition of the profile line from the cloud of measured points and can be significantly different from the ones with envelope lines. The standard now fully defines other possible modifiers for determining the angular size of a feature divided into three groups: local angular sizes (2) and global angular sizes (2), which also include statistical sizes (7 rank order angular sizes).



Linear sizes ISO 14405-1 (LP) (SM)

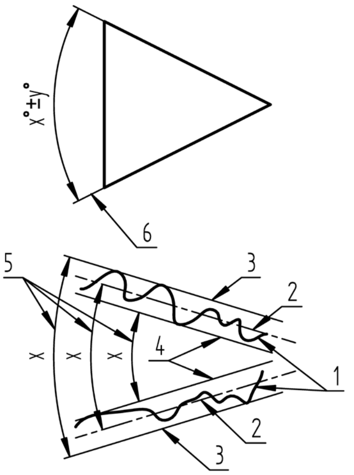
Fig. 1. *Example of explicit size specification and alternate defaults*

The standard introduces numerous new symbols that specify which operator (definition) applies to individual size measurements or generally to all size measurements on a product that does not have an explicit modifier (alternate defaults specified with the indication of ISO 14405 [17] and [19] and the appropriate modifier).

Tolerances of linear and angular dimensions are indicated on drawings or models according to the dimensioning rules (ISO 129-1:2018 [21]) as:

- upper limit deviations (ULD) and lower limit deviations (LLD) from the nominal dimension;
- upper limit sizes (ULS) and lower limit sizes (LLS);

- the ISO tolerance code of the internal or external size according to ISO 286-1:2010 (only linear dimensions) [23].



Angular sizes ISO 14405-3 (LC)

Notes:
1 real feature, 2 associated feature with minimax criterion without material constraint, 3 assoc. feature with minimax criterion with outside material constraint, 4 assoc. feature with minimax criterion with inside material constraint, 5 two-line angular size, and 6 angular dimension

Fig. 2. *Example of default angular size definition (Chebyshev)*

According to the rules given in ISO 14405, it is possible to use other operators of linear or angular size throughout the entire tolerance range (interval), or different types for the upper and lower limit sizes (Fig. 1). As new global size operators can affect both the size and shape of FoS, correlations between different specifications are created with such use, breaking the principle of independence. During verification, in this case it is necessary to perform various measurements that produce an interconnected result. This is similar to considering the well-known envelope principle (E) when dimensioning the size of shafts and holes. Although according to the ISO GPS philosophy, the envelope principle is not implicit (as it is in ASME Y14.5 - Rule #1), it is still often useful and represents a connected requirement for the ideal form of shafts and holes in a state where the product contains the maximum amount of material (MMS). It is also important to know that the envelope principle is no longer automatically included if we use ISO encoded tolerances of size for shafts and holes, but the envelope requirement always needs to be added explicitly or generally for all shafts and holes on the product (Fig. 1).

The operators that determine the definitions of statistical sizes are the same for linear and angular size measurements and represent typical statistical estimators, which are mainly used when defining statistical tolerances and also when defining statistical indexes in statistical process control (SPC). The calculation of statistical estimators is simple in size measurements, as the actual measurements are themselves independent scalar statistical variables. However, the use of these operators in size specifications does not automatically imply the adherence to statistical tolerance criteria for verifying these measurements. The documentation must state explicitly and unambiguously that a certain dimension must be verified using the principles of statistical tolerancing.

Caution should also be exercised when performing tolerance analyses, as the known methods do not necessarily include the adapted rules from the existing standards. The same applies to software tools, for which it is generally difficult to determine the standards with which they fully comply.

ISO 14405-2:2018 [18] lays down guidelines for specifying tolerances or dealing with other linear or angular dimensions that do not represent size, in terms of specification unambiguity. This refers to dimensions that represent:

- various linear distances between features that are not between two opposite points;
- linear dimensions that represent the distance between two different integral features;
- rounding radii;
- angular dimensions representing orientation between two different features (reference and feature).

The use of dimension tolerances (using limit deviations, limit dimensions, or ISO tolerance code) can be ambiguous in these cases and is not recommended. Only suitable geometrical tolerances should be used for all such geometrical characteristics.

3 GEOMETRICAL TOLERANCES

The principles and rules governing the narrower area of GPS, known in ASME as GD&T, are regulated by numerous ISO standards. Over the past 10 to 15 years, many new standards have been adopted, and many existing ones have undergone fundamental revisions, enabling new ways of specifications that were previously undefined. In the far past, many of them were probably adopted from ASME standards, but later they evolved in ISO along a slightly different path. Nevertheless, both systems are very close and similar, with a few significant differences **[4]**, **[5]** and **[11]**.

Several individual standards from the former global ISO GPS group are essential for a comprehensive and in-depth understanding of the concepts, which we will not discuss in detail (**[25]** and **[58]** to **[65]**). Below described are the essential standards for everyday practical use which belong to the group of general standards.

GTs are organized into four groups depending on what geometrical characteristics they specify and thus control for the selected feature (Table 3):
- form,
- orientation,
- location, and
- runout.

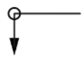
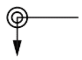
Table 3. *Geometrical tolerances (groups, symbols)* **[24]**

Group	Symbol	Tolerance, tolerance zone, datums (Yes/No)
Form	⏤	Straightness, 2D or 3D[1], No
	⏥	Flatness, 3D, No
	○	Roundness, 2D, No
	⌭	Cylindricity, 3D, No
	⌒	Line profile, 2D, No
	⌓	Surface profile, 3D, No
Orientation	//	Parallelism, 3D[2], Yes[3]
	⊥	Perpendicularity, 3D[2], Yes[3]
	∠	Angularity, 3D[2], Yes[3]
	⌒	Line profile, 2D, Yes
	⌓	Surface profile, 3D, Yes
Location	⌖	Position, 3D, Yes[4]
	◎	Concentricity or Coaxiality, 3D, Yes[4]
	⌯	Symmetry, 3D, Yes[4]
	⌒	Line profile, 2D, Yes[4]
	⌓	Surface profile, 3D, Yes[4]
Run-out	↗	Circular runout, 2D, Yes[5]
	⌰	Total runout, 3D, Yes[5]

1 for median axes
2 generally 3D, can be converted to 2D with additional modifiers
3 single datum or system of 2 datums (block at least 4 to 5 degree of freedom (DoF))
4 full datum system (block 6 DoF)
5 datum/datum system must establish an axis of rotation

The first three groups of GTs include tolerances, which, along with size tolerances (according to ISO 14405 **[17]** and **[19]**), can fully control (supervise) the basic geometrical characteristics of rigid bodies: their size, permissible form deviations, orientation, and location in 3D space. Given these characteristics, the geometry in 3D space is fully defined. GTs are organized hierarchically: their requirements are increasing, which means that costs increase as well. Therefore, economic logic dictates that we choose the largest tolerance zones for location GTs, smaller for orientation, and the smallest for form GTs.

Table 4. *Additional GT symbols (modifiers) – excerpt from ISO 1101* **[24]** *and ISO 1660* **[34]**

Symbol	Description
	Combination specification elements
CZ	Combined zone
SZ	Separate zones
	Unequal zone specification elements
UZ	Specified tolerance zone offset
	Constraint specification elements
OZ	Unspecified linear tolerance zone offset (offset zone)
VA	Unspecified angular tolerance zone offset (variable angle)
	Associated toleranced feature specification elements
Ⓒ	Minimax (Chebyshev) feature
Ⓖ	Least squares (Gaussian) feature
Ⓝ	Minimum circumscribed feature
Ⓣ	Tangent feature
Ⓧ	Maximum inscribed feature
	Derived toleranced feature specification elements
Ⓐ	Derived feature[1]
Ⓟ	Projected tolerance zone
	Toleranced feature identifiers
UF	United feature
LD	Minor diameter
MD	Major diameter
PD	Pitch diameter
◄►	Between
	All around (profile)
	All over (profile)
	Auxiliary feature indicators
ACS	Any cross-section
SCS	Specified cross-section
◁// B	Intersection plane indicator
◁// B▷	Orientation plane indicator
←// B	Direction feature indicator
○// B	Collection plane indicator

1 alternate indication of median axes and planes as toleranced feature

The basic standard is ISO 1101:2017 **[24]**, which sets out the basic rules and symbols for using geometrical tolerances for form, orientation, location, and runout. The standard defines 14 different geometrical tolerances (cf. Table 3), which can be applied to integral or derived features (median lines or surfaces of FoS), and can have 3D or 2D tolerance zones.

Depending on the type of GT, numerous additional tolerance symbols (modifiers) can be used which unambiguously define the shape and size of the tolerance zone and determine whether the principle of independence or other correlations applies between individual parts of the zone. Geometrical tolerances for form and profile are defined in detail in separate standards.

The default definition of all GTs is that all extracted (measured) [25] points on the toleranced feature of the real product must be within the boundaries of the tolerance zone. However, before assessing (verifying) whether the feature is within the tolerance zone, it is now possible to use various mathematical procedures on the cloud of these points, such as various filtering and association of ideal mathematical features according to the selected mathematical definition (e.g., tangent plane, envelopes, Gaussian or Chebyshev line or surface; Table 4). By default, the assessment is carried out using the default definition of tolerancing (also known as “worst-case tolerance”), but it can also be carried out according to the statistical principle. In this case, however, certain issues arise, which will be discussed later.

3.1 Form GTs

Form GTs are basically determined in the widely used ISO 1101 [24] standard and defined in more detail in specific standards (straightness (2D) [30], and [31], flatness (3D) [32] and [33], roundness (2D) [28] and [29] and cylindricity (3D) [26] and [27]). They can control deviations from the ideal form for elementary geometrical features (straight line, flat surface, circular line, and cylindrical surface). However, they cannot control their size, orientation, and location. The group of form tolerances also includes line profile and surface profile [34] tolerances, when used without references (datums).

3.2 Orientation GTs

Orientation GTs (parallelism, angularity, and perpendicularity [24]) are also primarily intended for elementary geometrical features (straight lines, flat surfaces) and mainly control the orientation relative to the reference (datum). In principle, one datum is enough, but for repeatability of measurements, it is recommended to use two datums. According to the basic definition, all three orientation GTs have 3D tolerance zones, but with the use of appropriate additional indicators, they can be converted into 2D zones (tolerances apply independently for individual lines on surface feature). The theoretically exact orientation of the feature must be specified using the Theoretical Exact Dimension (TED) in the datum system. Orientation GTs cannot control the size of the features and their locations in space, but they can indirectly (secondarily) control the form, although this is not their primary purpose.

3.3 Location GTs

Location GTs (position, concentricity or coaxiality, and symmetry) are primarily intended for derived FoS features (axes, median planes) and control their location in the coordinate system, which is determined by the reference system (datums). According to ISO, these tolerances can also be used to control individual integral features (lines, planes). By default, these tolerance zones are three-dimensional (3D), and the theoretically exact location of the characteristic must be dimensioned using TED in the datum system. The datum system must be complete and lock all degrees of freedom (DoF) of movement of rigid bodies (three translations and three rotations). The sequence of single datums in the datum system (primary, secondary, and tertiary) allows for the reproducible establishment of these datum coordinate systems and therefore reproducible measurements. Except for the size of the selected feature, location GTs control all geometrical characteristics: primarily the location, indirectly (secondarily) the orientation, and indirectly (tertiary) the form.

The position tolerance (ToP) has historically been the most frequently used geometrical tolerance (over 60 %). The reason for this is that the position of the FoS is critical to ensure the assembly of components (production and maintenance economics) and often also has a significant impact on the function of the assemblies. This tolerance is mostly used to control the position of median axes or median planes of shafts and holes (FoS). Such usage also meets the condition for the application of additional material requirements (MMR, LMR, RRP), which further can reduce production and control costs with the use of fixed gauges.

3.4 Material Requirements

Material requirements can be used with location tolerances and orientation tolerances, and even with certain form tolerances (straightness, rarely flatness), when these are applied to derived features (median axes and planes) of FoS. Details on material requirements are regulated by the ISO 2692:2021 standard [35] (Table 5).

Table 5. *Additional GTs modifiers - ISO 2692 [35] and ISO 10572 [50]*

Symbol	Description
	Material condition specification element [35]
Ⓜ	Maximum material requirement (MMR)
Ⓛ	Least material requirement (LMR)
Ⓡ	Reciprocity requirement (RPR)
	State specification element [50]
Ⓕ	Free state condition (non-rigid parts)

All material requirements mean a certain interconnection of the tolerance of the size dimension of the FoS and geometrical tolerance, thereby eliminating the principle of independence. With these requirements, potential increases in the deviation of the geometrical characteristic may occur when the size of the FoS (shaft or hole) approaches the opposite limit size at which the product with this FoS contains the maximum (MMR) or minimum (LMR) possible amount of material. This increase is called a "bonus" tolerance (originating from the tolerance of the linear size dimension of the FoS).

The reciprocity requirement (RPR) is an additional requirement, which may be used together with the maximum material requirement (MMR) and the least material requirement (LMR) in cases where it is permitted — taking into account the function of the toleranced feature(s) — to enlarge the size tolerance when the geometrical deviation on the actual workpiece does not take full advantage of, respectively, the maximum material virtual condition or the least material virtual condition.

The reciprocity requirement (RRP) is less well-known in practice and is rarely used. The permitted increase in the size tolerance, however, arises from the specified value of the tolerance zone of the used GT.

The MMR and LMR requirements can also be used for datums if these are also derived FoS (axes, median planes). Such use brings an additional bonus to the size of the GT tolerance zone, which is called "datum shift" (as it arises from the tolerance of the linear size dimension of the datum FoS). The logical and correct use of the MMR requirement for both the controlled FoS and the datum FoS at the same time allows the manufacture and use of complex entirely mechanical verification control devices (gauges) of fixed size (calibres), with which we quickly check the appropriateness of geometrical characteristics according to the principle of "accepted or rejected".

All material requirements can reduce production costs in serial production. However, caution is needed when the characteristics being toleranced are key to assembly or function, as they increase the total tolerance and thus possible variations in the geometrical and/or size characteristic between the limit values (greater scatter), which development engineers must take into account.

3.5 Profile GTs

The two geometrical tolerances of the profile (line and surface profile) are added to each of the basic three groups of tolerances for controlling form, orientation, and location.

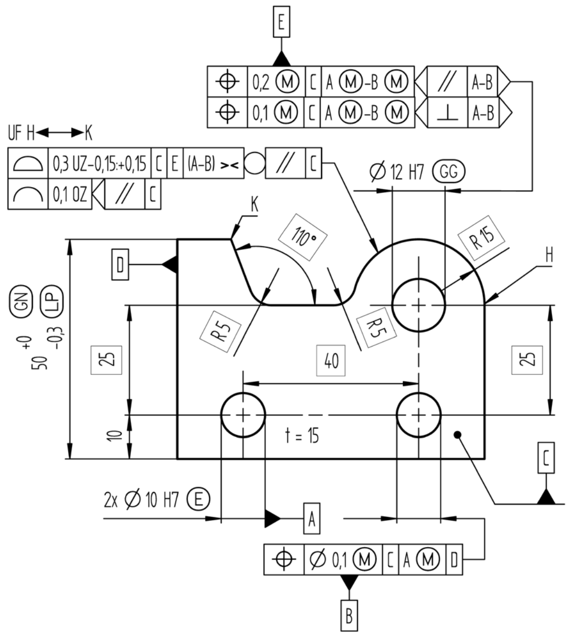


Fig. 3. *Example of complex GT specifications (ISO GPS system)*

These two tolerances rank among some of the most universal GTs and can control almost anything through an appropriate use of additional indicators and datums (Fig. 3). Therefore, profile GTs are becoming, along with the position tolerance, the most widely used GTs and are also well suited to the modern methods of geometry control and measuring equipment, which allow measurement of the absolute coordinates of each point on geometrical features. All these possibilities are detailed in the rules of the ISO 1660:2017 standard [34], which has been thoroughly updated compared to the previous edition. In the future, with all the changes and innovations, these two tolerances will undoubtedly joint the position tolerance in the group of the most commonly used GTs.

3.6 Runout GTs

The geometrical tolerances for circular runout and total runout are still categorized in a separate group, even though by definition, they allow control over the form, orientation, and position of the toleranced feature. The definitions of both tolerances are based on the characteristic rotational movement of many machine elements or their features and were used for verification even before the GDT system was even regulated in various standards. In the past, the methods were known under the names “full indicator reading” (FIR) and “total indicator reading” (TIR).

When using runout tolerances, the following rules apply:

- Both tolerances can only be used for integral features, never for derived features (median lines and planes).
- In this case, a datum or datum system is mandatory as it establishes a clear rotational axis around which we must physically rotate the toleranced feature in its entirety (360°) or in a restricted area in which this feature is defined. In principle, we can also rotate the measuring probe around the axis of this feature.
- The measuring probe used to extract points on the feature during verification must constantly touch, or slide along, this feature.
- The movement of the probe in the direction of the normal line on the feature or in the direction that must be clearly specified (using the appropriate additional tolerance indicators or modifiers) is compared with the specified width of the tolerance zone.

The circular runout tolerance means measurement in a cross-sectional plane that is normal to the rotational axis, the tolerance zone is two-dimensional (typically, a circular ring). The measurement of the circular runout deviation over the entire surface is carried out when moving along the rotational axis; each measurement is independent of the others.

The total runout tolerance involves the same method of measurement, except that during measurement we move the cross-sectional plane along the rotational axis so that we cover the entire surface, and the measurements are dependent on each other. Therefore, the tolerance has a 3D tolerance zone (rotational volumetric ring).

Both runout tolerances represent the control of form and orientation, and in special cases, also the position of the toleranced feature. However, they generally do not control size. Verification is effective but generally requires special measuring equipment, which is usually only available in workshops that produce characteristic “rotational” products in series. In principle, we can achieve similar effects with the alternative use of other geometrical tolerances.

3.7 Datums and Datum Systems

References or datums are key to all GT with which we control the location and/or orientation of geometrical features, and to runout tolerances. With the help of datums, we create a global and/or local coordinate system, within which the tolerance zone of GT is precisely positioned and oriented (Table 6). The rules for specifying and practically establishing datums, and thus reference coordinate systems, are described in detail in ISO 5459:2011 [36].

Table 6. *Symbols and additional datum indicators - excerpt from ISO 5459* [36]

Symbol	Description
	Datum features and datum target indicators
▶A	Datum feature indicator (capital letters A, B, C, AA, etc.)
⊖	Single datum target frame
◁⊖	Moveable datum target frame
×	Datum target point
-··—··—··-	Datum target lines, borders…
	Datum modifiers symbols (excerpt)
[PD]	Pitch diameter
[MD]	Major diameter
[LD]	Minor diameter
[ACS]	Any cross section
[ALS]	Any longitudinal section
[CF]	Contacting feature
[DV]	Variable distance (for common datum)
[PT]	(situation feature of type) Point
[SL]	(situation feature of type) Straight line
[PL]	(situation feature of type) Plane
><	For orientation constraint only
Ⓟ	Projected tolerance zone (for secondary or tertiary datum)
Ⓛ	Least material requirement
Ⓜ	Maximum material requirement

Datums are stated on technical drawings or models (MBD) which display the TEG and whose sizes correspond to the dimensioned nominal dimensions. Datums can be individual (e.g., A) or common (e.g., A-B), and both types can form datum systems.

However, for verification, datums need to be established from the real geometry features of the product with all possible and permissible errors. One of the principles is that it is appropriate to first ensure, using the form and orientation GTs, that these features also have suitable quality (flatness, straightness, etc.) after manufacturing. A Cartesian coordinate system is most easily created with three planar datums that are orthogonally oriented to each other, but other combinations are also possible. Such a datum system locks all degrees of freedom of movement (three translations, three rotations) of a rigid body, which is a necessary condition when needing to control all geometrical features, primarily with location. When only orientation needs to be controlled, it is enough that four or five degrees of freedom are locked. When using datum systems, the sequence (primary, secondary, tertiary) in the tolerance frame is crucial as it also allows for repeatable insertion of the product into the gauge, thus ensuring repeatable and comparable measurements.

Datums for verification can be established using mechanical measuring tools and accessories (tables, support elements, etc.). At least one suitable primary datum system defined on the product should be of such a type that it can be used to position products in measuring devices. The primary single datum in the datum system should ideally support the weight of the product.

Datums can also be established mathematically from clouds of measured points. In doing so, various operations previously described in the characteristic specifications can be used to determine a proper mathematical feature from a cloud of points that will be used to establish the datum. The current standard allows for the use of operations similar to those applicable for toleranced features (filtering [24], ISO 16610 [37] series, associations, etc.). It also offers several ways to limit the extent of features used for datums (datum targets). If a derived feature (e.g., an axis) is chosen for an individual datum, it is also possible to use material requirements and the appropriate simulation of the datum (e.g., with fixed mechanical aids in the case of MMR). It can also be set which characteristics each datum can be used for and which degrees of freedom it should lock.

All these possibilities are foreseen in the current version of the standard, which today allows for an unambiguous definition of practically useful datums based on the state of measurement technology. Various additional requirements (modifications) that need to be taken into account are typically written in the definition and use datums with appropriate indicators written in square brackets (e.g., [CF], [DV], [VA], etc. Fig. 4) and new symbols used on the drawing or 3D model (e.g., movable datum targets).

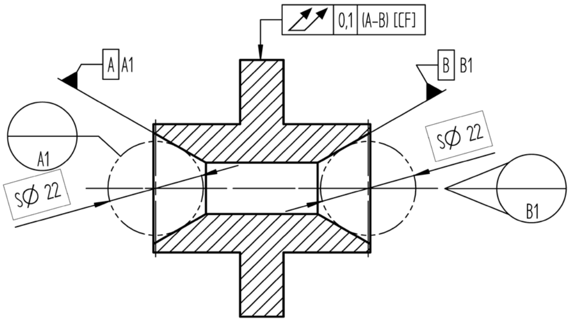


Fig. 4. *Example of datum system specification using a movable datum target and contacting feature [CF]*

3.8 General Tolerances

The general principles of ISO GPS (ISO 8015 [14]) also include the general specification principle and the definitive drawing principle. The first speaks to the fact that for each product it is possible to explicitly specify every one of its characteristics, while the second indicates that general specifications (dimension tolerances, GT, surface conditions, edge states) must be determined for all characteristics without explicit specifications. The second principle speaks to the fact that we cannot demand the executor (workshop) to make anything that is not unambiguously defined on the drawing in an explicit or general way.

General specifications are therefore a very important part of technical documentation. In ISO GPS, this issue is regulated with a series of general standards, which must be appropriately listed or used in the documentation:

- ISO 22081:2021 [38] is a new standard that sets out the principles and rules on how to specify general dimensional tolerances and general geometrical tolerances on documentation. It is recommended that this standard is explicitly mentioned in the documentation and that it is detailed within this mention whether the general tolerances are:

- linear size dimension tolerances;
- angular size dimension tolerances; or
- geometrical tolerances (it recommends the exclusive use of surface profile tolerance with a complete reference system of plane datum system; R, S, T).

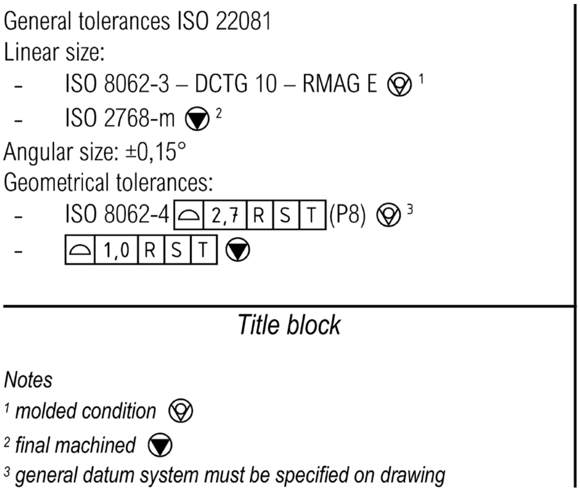


Fig. 5. *Example of general tolerances specification* [38]

Each of these can be determined individually and with their own constant values or own table for a larger size range, or we can refer to another appropriate standard in which the values are already determined according to the selected quality class defined in this standard.

- ISO 2768-1:1989 [39] is the basic standard for general tolerances of linear and angular dimensions (sizes) of products, which are mainly produced using cutting technologies (machining). Typically, the permitted deviations depend on the size of the dimension (eight intervals from 0.5 mm to 3150 mm) and on the required quality (four classes: fine, medium, coarse, and very coarse). As with all general tolerances, the tolerance interval is centred around the nominal value of the dimension. This, of course, means that dimensions controlled by general tolerances are entirely unsuitable for forming various fits between parts (shafts and holes), as the fit is impossible to predict. The second part of this standard governed certain general geometrical tolerances and was outdated and therefore withdrawn in 2021.
- ISO 8062 [40] to [43] specifies general specifications for castings made from metal alloys. The standard is issued in several parts and regulates vocabulary, rules, general tolerances for linear dimensions (DCTG in 16 quality grades), general geometrical tolerances (GCTG – surface profile tolerance based on the full general datum system R, S, T in 15 grades) and sizes of required machining allowances for subsequent mechanical processing (RMAG in 10 quality grades). The size measurement interval is in sub-intervals up to 10,000 mm, and the corresponding quality levels depend on the type of material and casting technology.
- ISO 20457:2018 [44] is a standard that sets general tolerances for general plastic castings and is very similar to ISO 8062 in principles and rules. However, it also provides guidance on product acceptability conditions and allows the selection of suitable specifications that correspond to the chosen type of material and plastic casting technology. The standard is issued under the auspices of ISO/TC 61/SC 2.
- ISO 13920:2023 [45] is a standard that sets general tolerances for length and angle measurements as well as form and orientation (flatness, straightness, parallelism), and positions of parts of welded constructions. The standard is issued under the auspices of ISO/TC 44/SC 10 and is conceptually somewhat different from what is presented in the current principles and rules of ISO GPS. It focuses on the main errors that occur in welding technology.

4 OTHER GPS STANDARDS

In addition to the standards described earlier in the paper, it is necessary to mention several commonly and widely used standards and specific ISO GPS standards from the group of general geometrical specification standards which are less frequently used but contain certain useful and effective principles and rules.

- ISO 16792:2021 [66] is a standard that falls into the TPD group and operates under the auspices of ISO/TC 10. However, it is inextricably linked with the group of GPS standards as it sets out the principles and rules on how to specify geometrical specifications in accordance with the MBD philosophy directly in 3D CAD models of products.
- ISO 10579:2010 [50] is a global GPS standard that sets out principles and rules for tolerancing parts that are not rigid and deform during verification under the influence of gravity differently in different orientations.

- ISO 21920:2021 [46] to [48] is a new standard in three parts that sets out profile specifications for the texture and condition of surfaces (roughness, waviness) and replaces ISO 1302, which has been withdrawn.
- ISO 13715:2017 [49] is a standard under the auspices of ISO/TC 10 that specifies allowable conditions ("chamfering or rounding") of sharp edges (external and internal) that are modelled as ideal.
- Less frequently used standards include, for example, standards used to specify and control certain characteristics on workpieces produced using special technological processes (e.g., castings [51]), local and limited imperfections on surfaces [52], conical and pyramidal (wedge) shapes [53] to [56], patterns [57] etc.
- ISO 20170:2019 [67] is a new and important standard from the group of fundamental ISO GPS standards. It describes principles and tools to control a manufacturing process in accordance with a GPS specification. For this purpose, a set of one or more complementary, independent characteristics (size, form, orientation, and location characteristics independent to each other) that correlate to the manufacturing process parameters and to the manufacturing process coordinate system established from the manufacturing datum system are used. This standard describes the concept of decomposition of the macro-geometrical part of the GPS specification. It does not cover the micro-geometry, i.e., surface texture. The objective of the decomposition is to define correction values for manufacturing control or to perform a statistical analysis of the process. In order to carry out SPC, it is inevitable to monitor the selected and most influential size dimensions and also geometrical tolerances on the basis of calculated statistical process capability indices (such as *Cp*, *Cpk*, etc.), and not merely based on verification whether the toleranced features are within the tolerance zone or not (classic tolerance definition). For size dimensions, which behave as independent scalar statistical variables during verification, these indices are easy to calculate (also with the help of new statistical operators of size definition according to ISO 14405). However, geometrical tolerances can be complex specifications (operations) that cannot be mathematically represented by a single scalar statistical variable. For SPC, it is necessary to mathematically decompose each GT into a list (vector) of scalar statistical components. This standard is the first to provide clear starting points, a mathematical basis (geometrical transformations), methods and rules for this decomposition. In this way, each geometrical specification can be fully monitored according to the principles of SPC.

5 CONCLUSIONS

This paper provides an overview of the philosophy of geometrical product specifications which is embodied in the ISO series of GPS (ISO/TC 213) standards. The principles and basic rules for clear and unambiguous specification of all requirements related to the geometrical features of products are divided into fundamental, general and complementary ISO GPS standards.

A clear and unambiguous geometrical specification which belongs to the basic pillar of GPS enables unambiguous product verification based on the principle of duality, thus facilitating the negotiation and communication process between the parties, i.e., the client and the supplier, in the process of designing and manufacturing mechanical products.

In the last two decades, ISO has made comprehensive and significant progress in this area, with many standards being amended and improved. The regulated specification of geometrical requirements with innovations in standards also enables a clear and unambiguous definition of necessary operations in verification, which better correspond to modern measurement methods and measurement technology based on the absolute measurement of the location of individual points in the cloud of extracted points on geometrical features of real products (CMM, optical and laser scanning, etc.).

Since these are important basics of technical communication, users should be well acquainted with them. This is often not the case, as it is a rather extensive topic with many novelties and frequent changes, causing considerable effort and thus problems for practical users in training. Due to the vast and varied scope of standards, engineers find it difficult to keep up with their dynamics in practice. Another issue is the accessibility, or the cost, of standards for users. This causes numerous problems since the communication between partners (client and supplier) often does not occur on the same basis.

In this paper, we focused primarily on geometrical specifications and the standards that regulate the geometry and sizes of products. There are also novelties in the field of surface texture and edge state specifications, which are mentioned but not explained in detail. Likewise, the entire parallel pillar of verification is omitted from the discussion. According to the ISO GPS matrix, the verification pillar contains an even larger number of standards that regulate verification in more detail.

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