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Geometrical Tolerances—Separate, Combined or Simultaneous?

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Abstract: The 14 geometrical tolerances defined in ISO 1101 are supplemented by the alphanumerical symbols defined in this standard and some other standards. The symbols CZ (combined zone), SZ (separate zones) and SIM (simultaneous requirement), which are crucial for the development of robust measuring programs for coordinate measuring machines, were introduced at different times or in different standards. It is shown that the symbol definitions are not always complete. Sometimes there are no univocal rules for their use, which, in some cases, leads to ambiguity in the specifications given by a designer. It is also pointed out that certain functional requirements can be controlled by different symbols, and it is not always clear if the indications are equivalent. This makes it difficult to understand and interpret a drawing by a metrologist and, thus, may lead to uncertainty in the assessment of product conformity regarding specifications. The identified ambiguities and problems in the specification of functional requirements are shown in several figures. Corrections and additions to current standards are proposed.

Keywords: geometrical tolerancing; Geometrical Product Specifications; ISO GPS system; ISO 1101; ISO 5458; combined zone CZ; simultaneous requirement SIM; GD&T

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Citation: Humienny, Z. Geometrical Tolerances—Separate, Combined or Simultaneous? *Appl. Sci.* **2023**, *13*, 6106. https://doi.org/10.3390/app13106106

Academic Editors: Krzysztof Stepien and Numan M. Durakbasa

Received: 10 April 2023
Revised: 12 May 2023
Accepted: 15 May 2023
Published: 16 May 2023

1. Introduction

Since 1996, when Technical Committee ISO/TC 213 *Dimensional and Geometrical Product Specifications and Verification* [1] was established, it has been conducting extensive work to develop and improve standards that address geometrical tolerances [2,3]. The aim is to provide contradiction-free rules and operators that allow designers to clearly and completely describe the acceptable variations of geometrical product characteristics such as size, orientation, location and run-out [4,5]. The capability of the existing tolerancing tools given in the ISO GPS system standards (ISO Geometrical Product Specifications system standards) is crucial both for classical machining and forming as well as for modern production methods such as additive manufacturing [6,7]. The ISO/TC 213 works are boosted by industries, mainly automotive and aerospace, that need indications to uniquely define how far the geometry of a manufactured part may be away from the nominal theoretically exact geometry and, when assembled, still operate according to the functional requirements.

The graphical symbols for 14 geometrical tolerances (characteristics symbols) are given and explained in ISO 1101:2017 [8]. The rules for geometrical specifications for integral and derived features, using the line profile and surface profile tolerance symbols, are detailed in ISO 1660:2017 [9] and in ISO 5458:2018 [10] are given complementary rules to ISO 1101:2017 regarding pattern specifications as well as rules to combine individual specifications. The pattern specification is a combined requirement, indicated by a set of geometrical specifications and controlled by a combination of more than one tolerance zones having, without priority between them, constraints of orientation and location or only constraints of orientation [10].

The 14 geometrical characteristics, with application rules defined in the standards listed above, are supplemented by the letter indicators given in these standards. Symbols such as CZ (Combined Zone), SZ (Separate Zones)—in the ISO GPS system, it is the default condition [11] and SIM (SIMultaneous requirement) were implemented at different times (e.g., in subsequent editions of ISO 1101) or in various standards. These letter symbols determine the meaning of the geometrical characteristic specified in the first section of the tolerance indicator, which is crucial when writing a measuring program for a coordinate measuring machine to verify a manufactured part's conformance with the particular specification.

It is underlined in [12] that geometrical variation management strongly relies on the gathering, processing, sharing and disseminating of tolerancing information that still requires many manual efforts and interventions. This paper aims to enable a complete understanding of what constraints are set when the CZ modifier is specified for a particular tolerance indicator and give recommendations for indications that secure univocal specifications. This is in line with the expectation that a reduction in the annotation contradictions, annotation redundancy, missing annotations and annotation uncertainty in the geometrical tolerances in Model-Based Definition (MBD)designing is the key to realising the digital integration of design, manufacturing and inspection [13].

The results of interesting research regarding the implementation of statistical tolerance analysis in the German industry are presented in [14]. Among other conclusions, the authors write that it is undisputed that revisions to and extensions of the ISO GPS system standards lead to a better and more accurate tolerance design as well as that the ISO GPS standards are met in the industry with great reluctance and scepticism due to their immense scope and complexity. Taking all ove the above into account, the purpose of this paper is to clarify issues with the univocal selection and functionally relevant tolerancing of a pattern of features.

2. New Rules That Reduce Specification Ambiguity

A vital example of the ambiguity and even outright contradiction found in the GPS standards for many years is the specification of the position or symmetry tolerance for a few toleranced features. In the past, it was a common practice that the adjacent indication (indication given above the tolerance indicator) defines the number of toleranced features (Figure 1) that generates the pattern. It was also stated that when two or more groups of features are shown on the same axis, they shall be considered to be a single pattern when they are not related to a datum or are related to the same datum or datum system. There are no unique arrangements in ISO 5458:1998 regarding the position tolerance for the rectangular pattern of holes. Therefore, designers and verifiers extrapolated the rules given for the circular pattern to rectangular patterns. On the other side, according to the *independency principle* (ISO 8015:2011 [11]), by default, every GPS specification for a feature or relation between features shall be fulfilled, independent of other specifications, except when it is stated in a standard or by a special indication added to a particular specification. Moreover, it was not clear whether the specifications given in Figures 1 and 2 are equivalent. According to ISO 5458:1998, indication 2× in Figure 1 creates one toleranced feature, whereas two separate indications for two features are given in Figure 2. It is not clear whether the pattern of two holes is defined in Figure 2, or two independent requirements are given. For the pattern, the two extracted median lines of holes with a nominal diameter of 10 mm shall be contained in two cylindrical tolerance zones with a diameter of 0.1 mm, the axes of which are located on the plane perpendicular to datum A, which passes through datum B. Datum A is established by the tangent plane to the disc's hidden surface. Datum B is established by the axis of the cylinder inscribed into the central hole with an orientation constraint (perpendicularity), with respect to the primary datum A. Moreover, cylindrical tolerance zones are located at the theoretically exact distance of 20 mm from datum B. For the two individual indicators extracted, the median line of each hole is independently considered and shall be contained in the cylindrical tolerance zone with a diameter of 0.1 mm, the axis of which is perpendicular to datum A and contained in the half plane that starts from datum B.

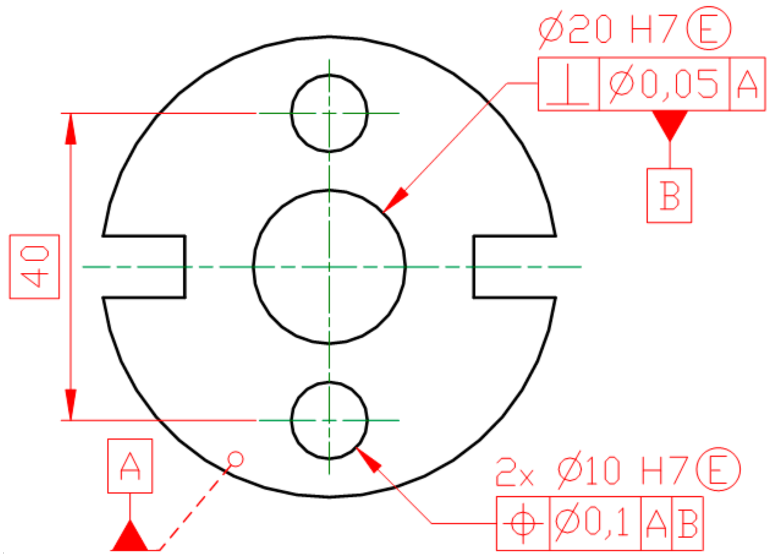


Figure 1. Position tolerance with one tolerance indicator for two holes—according to ISO 5458:1998, the holes, by default, constitute the pattern.

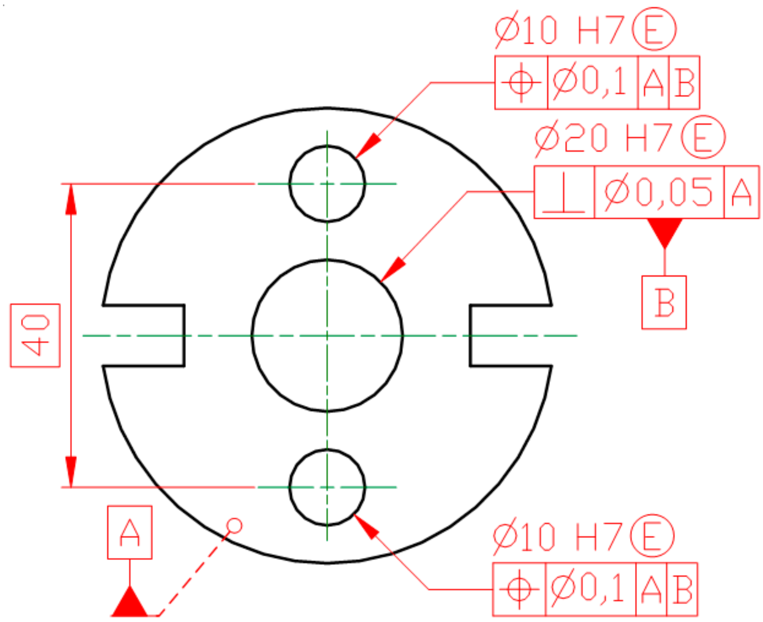


Figure 2. Position tolerance with two tolerance indicators individually given for two holes—lack of univocal meaning.

In the following figures, the possibilities for the unambiguous specifications of the various functional requirements regarding the relative locations of holes and grooves are shown. The rules and modifiers given in the latest edition of the revised ISO 5458, published in 2018, are used and discussed.

In Figure 3a, the axis of each individually considered cylindrical tolerance zone with a diameter of 0.1 mm for the position tolerance (the SZ modifier is indicated) is perpendicular to datum A—the tangent plane to the extracted datum's surface that is at a radius of 20 mm from datum B—which is the axis of the cylinder that is inscribed into the extracted central hole with a perpendicularity constraint with respect to datum A. The symmetry planes of the two pairs of two parallel plains establishing the individual tolerance zone with a width of 0.08 mm (the SZ modifier is indicated) for each groove are perpendicular to datum A and pass through datum B. The verification of the conformance with specification shall be independently performed (individually) for each of the four toleranced geometrical features (Figure 3b).

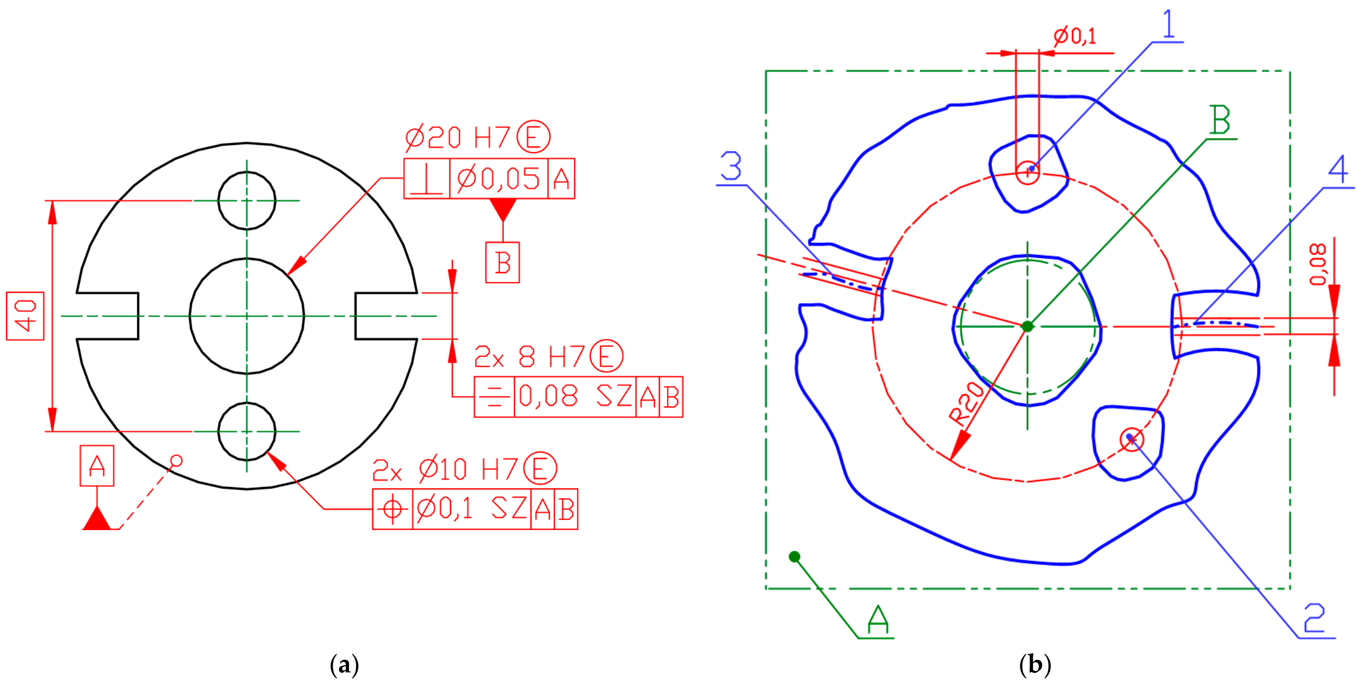


Figure 3. (**a**) Specification—there are no constraints for the angle between the toleranced holes. There are no constraints for the angle between the toleranced grooves. There are no constraints for the angle between the holes and the grooves. (**b**) The actual part that fulfils the specification from (**a**). Derived median lines of the top (1) and bottom (2) holes and derived median surfaces of the left (3) and right (4) grooves are in the tolerance zones. Each tolerance zone is separately established with respect to datum system A | B.

In Figure 4a, the two cylindrical tolerance zones for the position tolerance establish the combined tolerance zone (the CZ modifier is indicated)—their axes are located in one plane that is perpendicular to datum A and passes through datum B as well as the tolerance zone axes that are at a radius of 20 mm from datum B. The two tolerance zones for the symmetry indicator form the next combined tolerance zone (the CZ modifier is indicated). One common symmetry plane for the two pairs of two parallel plains establishing each of the two symmetry tolerance zones is perpendicular to datum A and passes through datum B (Figure 4b). This means that the actual part shown in Figure 3b shall be rejected according to the requirements given in Figure 4a.

In Figure 5a, the axes of the tolerance zones and the symmetry planes of the tolerance zones are located on two mutually perpendicular planes that are perpendicular to datum A and pass through datum B, as defined by the SIM modifier—the simultaneous requirement. Moreover, the axes of the cylindrical tolerance zones are at a radius of 20 mm from datum B. The use of a SIM modifier transforms a set of more than one geometrical specification into a combined specification (pattern specification). This means that the tolerance zones for all the given specifications are locked together with location and orientation constraints (Figure 5b). According to the requirements shown in Figure 5a, the actual parts shown in Figures 3b and 4b shall be rejected.

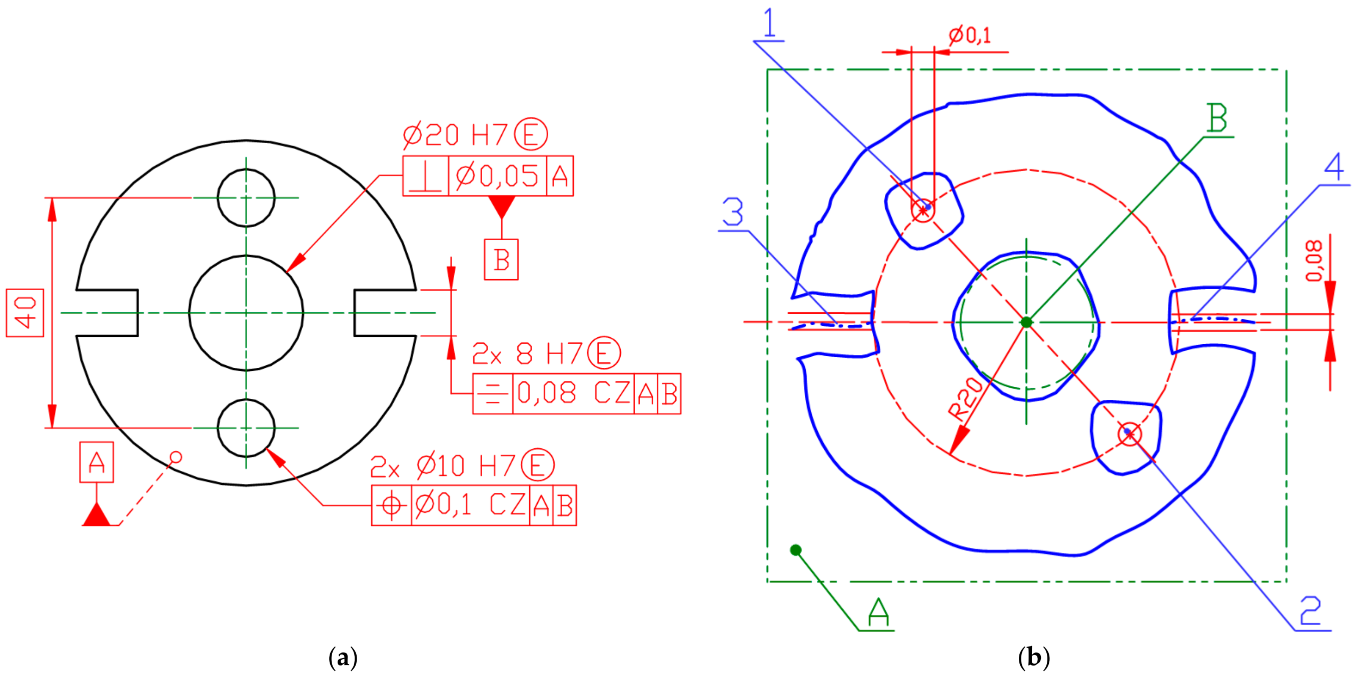
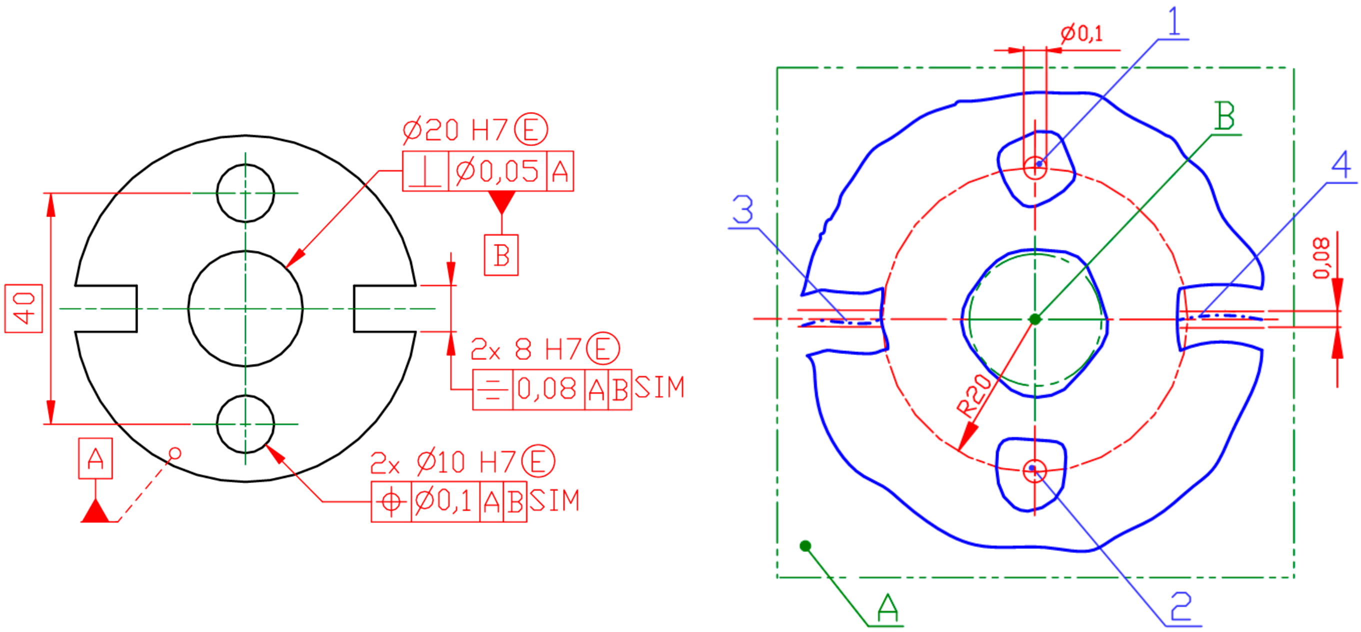


Figure 4. (**a**) Specification—two patterns, the pattern of two holes and the pattern of two grooves, are independently toleranced. There are no constraints for the angle between two individually toleranced patterns. (**b**) The actual part that fulfils the specification from (**a**). Derived median lines of the top (1) and bottom (2) holes and derived median surfaces of the left (3) and right (4) grooves are in the tolerance zones. Two cylindrical tolerance zones are locked between themselves, and, separately, tolerance zones established by two pairs of two parallel plains are locked between themselves.

The above discussion may be used to correct the specifications given in Figures 1 and 2. In Figure 1, the CZ modifier shall be added after the tolerance value T = 0.1 mm to set the pattern of two holes with a diameter of 10 mm. The CZ modifier determines that the tolerance feature is defined as the collection of two extracted median lines. The tolerance is the tolerance zone pattern composed of two cylindrical tolerance zones with a diameter of 0.1 mm, where their axes are perpendicular to datum A (implicit theoretically exact dimension, TED = 90° [8]), that are internally constrained in a location at a distance of TED = 40 mm apart and are diametrically opposed, i.e., the axes of the tolerance zones are located on the plane perpendicular to datum A that passes through datum B. Moreover, due to the CZ modifier, the tolerance zones are constrained in the location from datum B at a distance of 20 mm. Alternatively, as shown in Figure 1, when the SZ modifier (separate zones) is specified, each individual cylindrical tolerance zone shall be independently considered. This means that the angular location between the holes is not fixed. The axis of each tolerance zone is located in the half-plane that starts from datum B, but the angular location between the two half-planes is optional. In Figure 2, the SIM modifiers shall be indicated on the right side of the two position tolerance indicators specified for two holes with a diameter of 10 mm. The specification of the SIM modifiers transforms the specifications that are individually given for each hole with a diameter of 10 mm into the combined specification. It denotes that the tolerance zones for two holes are locked together with location and orientation constraints into the pattern specification. So, in the considered case, the specification of two SIM modifiers is functionally equivalent to the discussed specification with the CZ modifier. The specification of the SIM modifiers is not the best choice in this case, since the notation of the CZ modifier is concise. The specification of the SIM modifiers is necessary when the CZ modifier cannot be applied, i.e., when the tolerance values given by the tolerance indicators are different, the shapes of the tolerance zones are different or the nominal diameters of the toleranced holes are different.



(**a**) (**b**)

Figure 5. (**a**) Specification—the four tolerance zones, two cylindrical tolerance zones and two spaces between two parallel planes, are locked among themselves and with respect to the specified datum system. One pattern of tolerance zones is established by two combined tolerance zones. (**b**) The actual part that fulfils the specification from (**a**). Derived median lines of the top (1) and bottom (2) holes and derived median surfaces of the left (3) and right (4) grooves are in the tolerance zones. Two cylindrical tolerance zones and two tolerance zones established by two pairs of two parallel plains are locked together as one pattern.

3. Ambiguities in Specifications—New Challenges

In Figure 6, the flatness tolerance with the CZ modifier (combined zone) for two planes is shown, and, in Figure 7, the meaning of this requirement, which was already established in ISO 1101:2004, is illustrated (according to the terminology used at that time, when the CZ modifier was decoded as a *common zone*). Since then, this standard has been revised two times, but only the name of the modifier has been updated, so its meaning has not been changed. In ISO 1101:2017, it is stated that when the CZ modifier is indicated in the tolerance indicator, all the related individual tolerance zones shall be constrained in location and orientation amongst themselves using either explicit or implicit theoretically exact dimensions. Unfortunately, this statement is not univocal. The question is what recalls the constraints, in other words, what forces the restriction that, according to Figure 6, the established tolerance zone pattern is composed of two tolerances zones, which are the spaces between pairs of two parallel planes 0.06 mm apart that are constrained in orientation to be parallel (the implicit TED = 0°) and in location to be coplanar (the implicit TED = 0 mm). The flatness tolerance belongs to the group of form tolerances [8]. Therefore, the flatness requirement indicated by the flatness symbol does not introduce any constraints between the tolerance zones. The drawing user shall additionally identify, from the drawing of this part, the 0 mm distance between the surfaces for which the flatness tolerance is specified, but this distance is not recalled itself by the flatness tolerance symbol that completely defines the requirement.

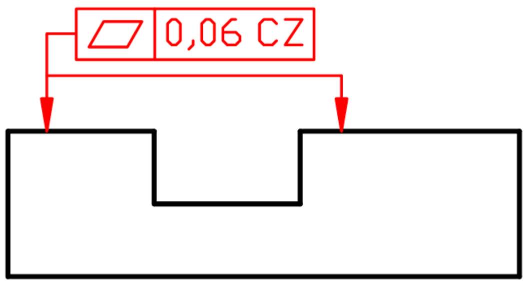


Figure 6. The flatness tolerance with the CZ modifier: two toleranced surfaces shall be considered together—widely used but not fully defining specification.

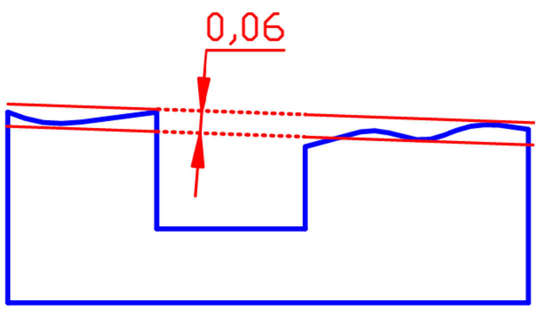


Figure 7. Two extracted surfaces shall be simultaneously contained between two pairs of two parallel planes with a distance of 0.06 mm that are coplanar—intended functional meaning.

In Figure 8, according to the provisions given in ISO 1101:2017 and ISO 14405-2:2018 [15], the position tolerance without a datum is indicated to set acceptable deviations for the relative location of two nominally planar surfaces. The position tolerance belongs to the group of location tolerances [8]. Therefore, such an indication recalls the theoretically exact dimension, TED = 12 mm, which is given explicitly in the drawing. This theoretically exact dimension sets a distance of 12 mm between the median planes of the two tolerance zones (Figure 9). After comparing the indications given in Figures 6 and 8, it seems evident that to keep the consistency and general approach in the specification meanings, the position tolerance shall be indicated instead of the flatness tolerance shown in Figure 6. Only the application of the position tolerance (Figure 10) recalls the theoretically exact dimension, TED = 0 mm, which is implicitly given in the drawing. Thus, the specification given in Figure 6 is definitely wrong, even ridiculous, because the flatness tolerance does not set any constraints between the tolerance zones. So the functional meaning shown in Figure 7 is not secured by the indication given in Figure 6, which is currently subjectively overinterpreted.

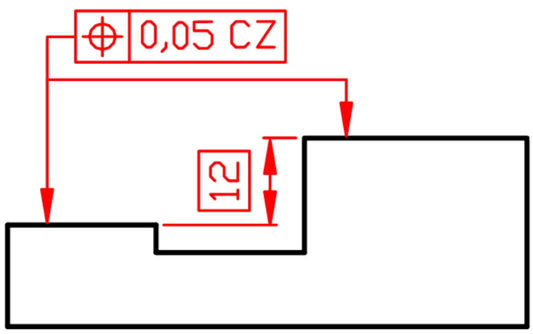


Figure 8. The position tolerance with the CZ modifier: two toleranced surfaces shall be considered together.

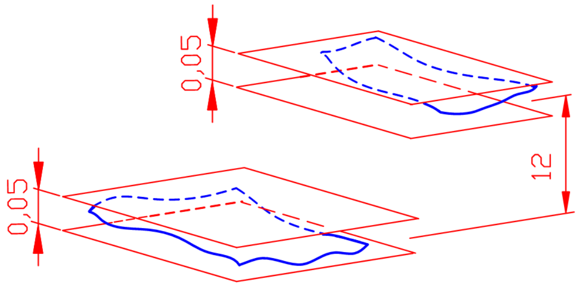


Figure 9. Two extracted surfaces shall be simultaneously contained between two pairs of two parallel planes with a distance of 0.05 mm and with a distance of 12 mm between their median planes.

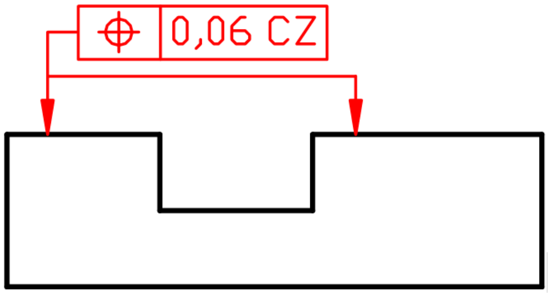


Figure 10. The position tolerance with the CZ modifier uniquely indicates that the two toleranced surfaces shall be coplanar—recommended specification that shall be used instead of the specification shown in Figure 6.

Similarly, according to the current industry indication and interpretation practice, it is assumed that the parallelism tolerance with the CZ modifier (Figure 11) constrains two tolerance zones for both surfaces in orientation to be parallel with respect to datum A (the implicit TED = 0°) as well as in location to be coplanar (the implicit TED = 0 mm). Datum A locks the part down on a surface that simulates datum plane A. It is important to emphasise that parallelism tolerance belongs to the group of orientation tolerances [8]. Therefore, the parallelism requirement indicated by the parallelism symbol does not introduce any location constraints between the tolerance zones. The drawing user shall additionally identify, from this part drawing, the 0 mm distance between the surfaces for which the parallelism tolerance is specified, but this distance is not itself recalled by the parallelism tolerance symbol that shall completely define the requirement.

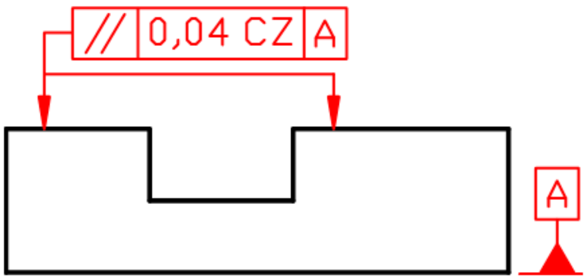


Figure 11. The parallelism tolerance with the CZ modifier: two toleranced surfaces shall be considered together—widely used but not fully defining specification.

To express in the univocal way the functional requirement illustrated in Figure 12, that both surfaces are fixed among themselves, the position tolerance shall be indicated. Such a specification enforces the implicit theoretically exact dimension, TED = 0 mm. The parallelism requirement for both toleranced surfaces with respect to datum A shall be defined using the modifier >< (for the orientation constraint only [8]) after datum identifier A in the tolerance indicator's third section (Figure 13).

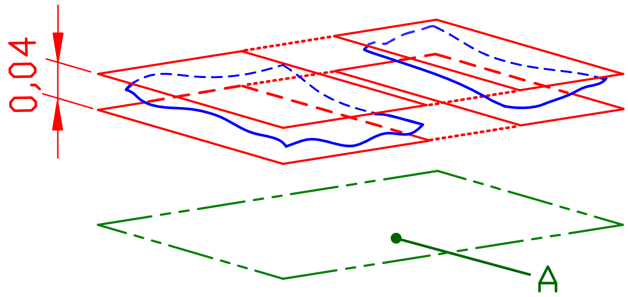


Figure 12. Two extracted surfaces shall be simultaneously contained between two pairs of two parallel planes with a distance of 0.04 mm and parallel to datum A—intended functional meaning.

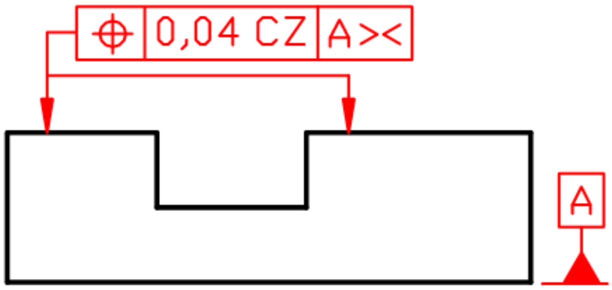


Figure 13. The position tolerance with the CZ and >< modifiers uniquely indicates that two toleranced surfaces together shall be parallel to datum A—the recommended specification that shall be used instead of the specification shown in Figure 11.

Another questionable example of pattern specification taken from ISO 5458:2018 [10] is given in Figure 14. In Figure 15, the current meaning of this specification is shown. The tolerance feature is a collection of two extracted median lines. The tolerance zone is a tolerance pattern composed of two cylindrical zones with a diameter of 0.1 mm, where their axes are constrained in location to be coaxial. Such an interpretation is not justified by the specification given in Figure 14. The straightness tolerance belongs to the group of form tolerances [8]. Therefore, the straightness requirement indicated by the straightness symbol does not set any constraints between the tolerance zones. The drawing user shall additionally identify, from this part drawing, the 0 mm distance between the axes of two holes for which the straightness tolerance is specified, but this distance application is not itself recalled by the straightness tolerance symbol that shall completely define the requirement.

The conclusion is that the position tolerance shall be indicated to specify the functional requirement depicted in Figure 15. Only the application of the position tolerance, as shown in Figure 16, recalls the theoretically exact dimension, TED = 0 mm, implicitly given by the narrow dashed-dotted symmetry line.

It is worth adding that the functional requirement depicted in Figure 15 may also be uniquely specified, as shown in Figure 17. The coaxiality tolerance for each hole with respect to the common data A–B is established by the specification in Figure 17. The coaxiality tolerance locates each cylindrical tolerance zone on the datum axis by the implicit theoretically exact distance, TED = 0 mm. So the two tolerance zones have the same axis that composes the tolerance zone pattern, as is required. The actual explanation is a bit more sophisticated due to the usage of a common datum (Figure 18).

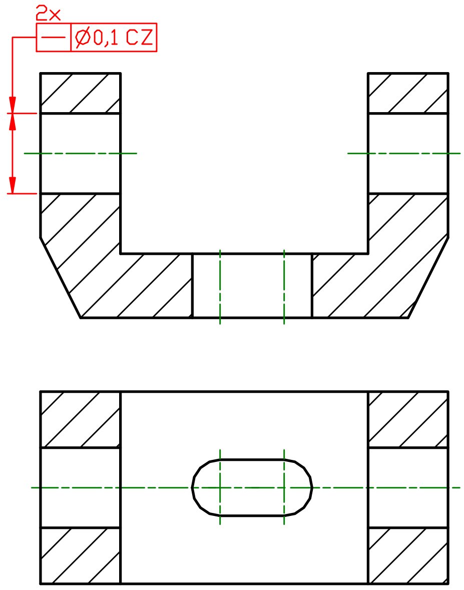


Figure 14. The straightness tolerance with the CZ modifier: two toleranced axes shall be considered together—widely used but not fully defining specification.

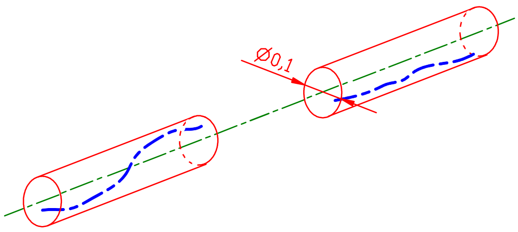


Figure 15. Two extracted axes shall be simultaneously contained in two cylinders with a diameter of 0.1 mm that are coaxial—intended functional meaning.

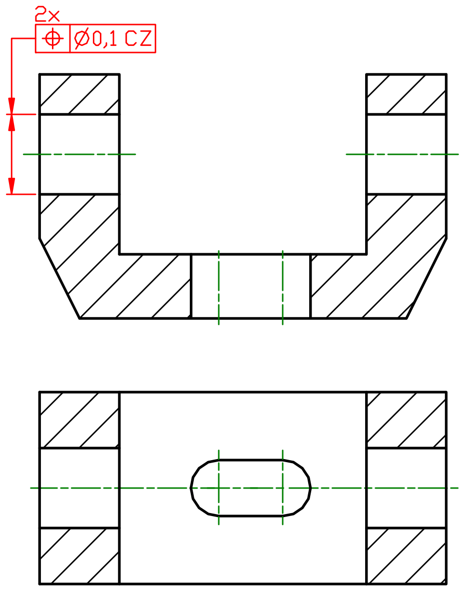


Figure 16. The position tolerance with the CZ modifier uniquely indicates that the two toleranced axes shall be coaxial—recommended specification that shall be used instead of the specification shown in Figure 14.

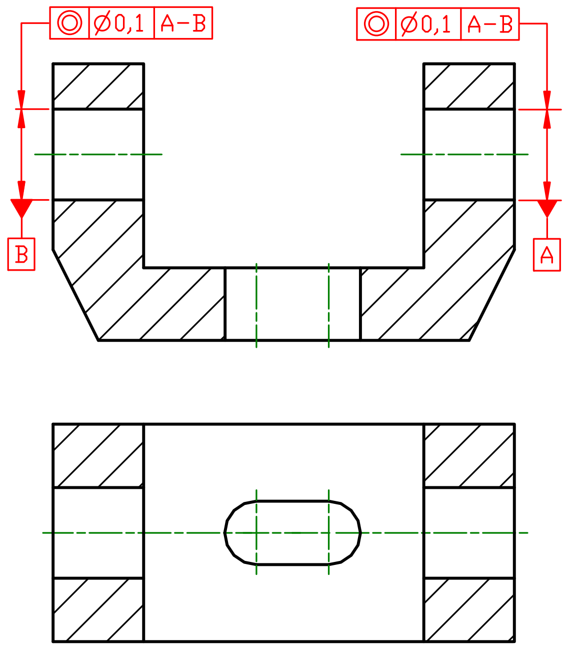


Figure 17. Alternative unambiguous specification for the functional requirement that is illustrated in Figure 15.

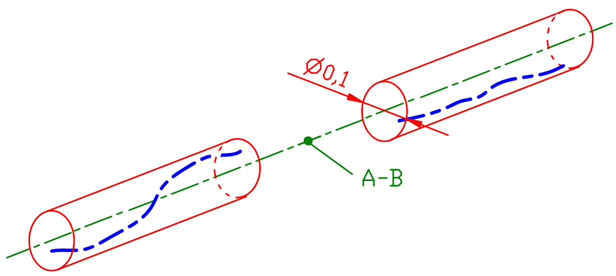


Figure 18. Formal meaning of the indication that is specified in Figure 17.

Regarding the current industrial practice for tolerances indication and interpretation, the specification given in Figure 19 is used to define the tolerance zone pattern composed of two coaxial cylinders with a diameter of 0.2 mm that are constrained in orientation to be perpendicular to datum A (the implicit TED = 90°), as shown in Figure 20. The problem is that the perpendicularity tolerance belongs to the group of orientation tolerances [8]. Therefore, the perpendicularity requirement indicated by the perpendicularity symbol does not introduce any location constraints between the tolerance zones. Only orientation constraints—implicit 90° (perpendicularity), implicit 0° (parallelism) and α (angularity with the explicit inclination angle)—are connoted by orientation tolerances. So the drawing user shall additionally identify, from this part drawing, the 0 mm distance between the axes of the two holes for which the perpendicularity tolerance is specified. This theoretically exact distance is not directly fixed by the perpendicularity tolerance symbol that shall completely define the expected functional requirement, and any additional analyses shall not be applied.

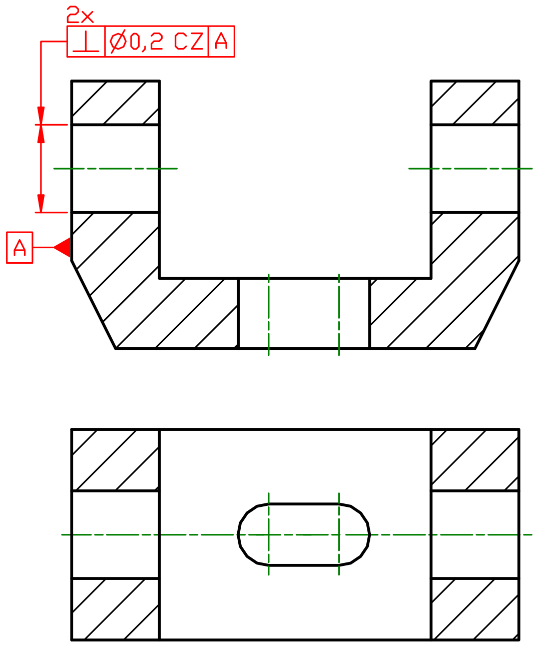


Figure 19. The perpendicularity tolerance with the CZ modifier: two toleranced axes shall be considered together—widely used but not fully defining specification.

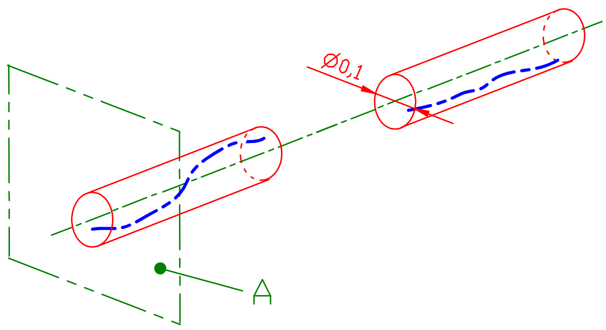


Figure 20. Two extracted axes shall be simultaneously contained in two cylinders with a diameter of 0.2 mm that are perpendicular to datum A and are coaxial—intended functional meaning.

To sum up, to specify the functional requirement depicted in Figure 20, the position tolerance shall be indicated. Only the application of the position tolerance, as shown in Figure 21, recalls the theoretically exact dimension, TED = 0 mm, which is implicitly given by the narrow dashed-dotted symmetry line.

Please keep in mind that although requirements similar to those illustrated in Figures 12 and 20 sound functional, i.e., when a designer wants to only specify the orientation constraint for a pattern of features with respect to a datum or datum system, Annex C to ISO 5458:2018 [10] does not contain any examples of such a specification. This can be considered as an accidental advantage of Annex C, although it can be found in Annex E of this standard, after a thorough analysis of the "Concept diagram for pattern specification and relation with modifiers", that the specification of a tolerance zone pattern with an orientation indicator for a pattern of features is permissible. It is hoped that the absence of examples of applications of the orientation tolerances will prompt some designers to apply location tolerances to secure functional requirements similar to those illustrated in Figures 12 and 20, which will give unambiguous specifications. The presence of examples of the form tolerances and the absence of examples of the orientation tolerances' applications for a pattern of features show the lack of consistency in ISO 5458:2018.

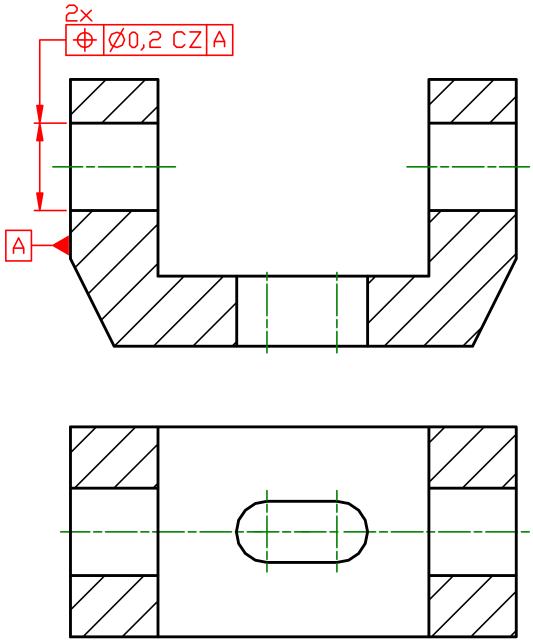


Figure 21. The position tolerance with the CZ modifier uniquely indicates that two toleranced axes together shall be perpendicular to datum A—the recommended specification that shall be used instead of the specification shown in Figure 19.

4. Conclusions

The ISO GPS system indications are important tools that help engineers communicate the tolerances of a product when designed. The indications shall clearly express all the design requirements and be precise to secure the consistent interpretation of the engineering drawings. The ambiguity in the specification may be due, inter alia, to the absence of provisions in the standards or may be due to the incorrect extrapolations/interpolations of the examples of the specifications given in the standards. Some erroneous specifications have become entrenched over the years during vocational training and lectures at universities as well as industry practices and are, unfortunately, constantly being repeated.

A pattern of holes or planes is quite often used as an assembly feature on a part. So the univocal tolerancing of such a set of features is a crucial designer task. According to the abovementioned issues, it is not recommended to specify a tolerance zone pattern for a group of features with a form or orientation indicator because the meaning of such a specification for a pattern is unclear. The form and orientation tolerances do not the fix linear theoretically exact dimensions between toleranced features. Therefore, they do not univocally distinguish the patterns of features. Only a location tolerance with a CZ modifier and a relevant datum or datum system (if required) unambiguously defines the constraints in a pattern. Therefore, it is strongly recommended to use position (symmetry) tolerance when a pattern of features is functionally required.

In the last decade, Technical Committee ISO/TC 213 *Dimensional and Geometrical Product Specifications and Verification* endeavours to eliminate the problem of the ambiguity in specifications by applying a new approach to standards development. Each new standard or revised edition of the standard that addresses geometrical tolerancing is rule-based. It contains a set of rules that generically define how the tolerances shall be specified and what their meanings are. Examples of the application of the rules formulated in each new or revised standard are given for a particular standard in its informative annex. Such an annex helps a user understand the rules given in the standard. On the other hand, the generic rules enable a user to indicate the tolerances for other cases according to the specific functional requirements. The great fundamental challenge for ISO/TC 213 experts is the effective formulation of rules in the standards, i.e., unambiguously and in a way that is easily understandable by all standard users.

It is worth understanding that some of the inconsistencies and contradictions highlighted and discussed in this paper are the subjects of vigorous dispute in Technical Committee ISO/TC 213. John Österlund, who works for the automotive industry, gave significant input [16]. Unfortunately, ref. [17] is an internal document of the ISO/TC 213 Working Group WG 18 *Geometrical Tolerancing* and is hardly available.

Each measurement requires the univocal definition of the measurand—the quantity that is intended to be measured. The rules and the modifiers provided in ISO 5458:2018 give designers new powerful tools to combine the individual specifications for geometrical features to create a pattern of features grouped with an external or internal location and/or orientation constraints. It should be emphasised, however, that some of the examples of pattern specifications given in Annex C (informative) of this standard need to be verified and corrected so that all constraints result only from the direct interpretation of the indication used and not from adopting additional assumptions that are not based on the rules given in the ISO GPS system standards. As shown in this paper, all constraints between the tolerances zones shall be identified by the ISO GPS system indications. The designer or drawing user shall not identify additional constraints from the part's CAD model.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable. The data are in the referenced standards.

Conflicts of Interest: The author declares no conflict of interest.

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