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ENVELOPE REQUIREMENT VERSUS PRINCIPLE OF INDEPENDENCY

Carmen SIMION, Ioan BONDREA
University "Lucian Blaga" of Sibiu, Faculty of Engineering “Hermann Oberth”,
e-mail:carmen.simion@ulbsibiu.ro, ioan.bondrea@ulbsibiu.ro

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Abstract: To ensure quality of technical goods and their production and assembly processes, regarding the function of each part, the designer sets its dimensions and other characteristics and also their tolerances. In this context, the international standardisation defines several principles and good practices for specifying tolerances. In this paper a definition of tolerance specification is given, the relationships between the different tolerance systems: the principle of independency and envelope requirement are explained and some applications of these tolerancing principles are introduced.

1. TOLERANCE SPECIFICATION

Regarding the function of a part, the designer sets its dimensions and other characteristics in a complex process by using his creativity, experience and knowledge. Additionally the designer defines the manufacturing route and the quality assessment of the components. The questions the designer initially is posed with during the design construction, deal with successfully fulfilling function of the component. A drawing which does not conform to the basic needs in a “complete” and “defined” manner can not be used as a basis for production and quality control.

Since the dimensions or other characteristics of a part cannot be exactly realized in manufacture, it must be given some kind of limit values, either on the drawing (preferably) or by reference to another document containing such limit values. These stipulate the values according to which the parts are to be approved or rejected. So, to ensure quality of technical goods and their production and assembly processes, the dimensions and the properties have to be limited and therefore toleranced. Tolerances are a communication of design, manufacturing, and inspection intent. Tolerance specification is here taken to mean each specification whereby the permissible variation for any property is given fixed limits. A tolerance specification includes those values which determine the limits for dimensions or other property. The tolerances shall be chosen so that they correspond to the functional and/or economical rejection limits.

In all cases, tolerances apply to features which are geometrical elements of a part, such as: lines, planes, circles, cylinders, cones, spheres, helixes, tore, and mathematically defined curves and surfaces (profiles). The main characteristics of a feature and a geometry are its size, form, orientation, and location. Size tolerances are referred to as dimensional tolerances, while form, profile, orientation, location and run-out tolerances are referred to as geometric tolerances [1] [4] [5].

Several principles and good practices for specifying tolerances are either explicitly defined or implied in the manufacturing tolerance standards. The principles help to ensure that: the functional, manufacturing and inspection intents are clear, the individual specifications form a consistent set of specifications with clear intent and priority, the specifications are realistic in the sense that they are producible and measurable, and unnecessary accumulation is minimized.

So, during the process of defining the tolerances of single parts or groups of components, according to ISO 8015, it must always be decided if the independence principle can allow for a toleranced size or if the envelope requirement has to be used. Additionally it must also be decided if a deviation of form or orientation, location or run-out has to be stated independently or if the maximum material requirement, minimum material requirement or reciprocity requirement can be allowed for certain geometrical tolerances. Beside the previously discussed principles of tolerancing, other conditions like the projected tolerance according to ISO 1101 or the free state according to ISO 10579 are used in technical drawings (Fig.1) [1] [3].

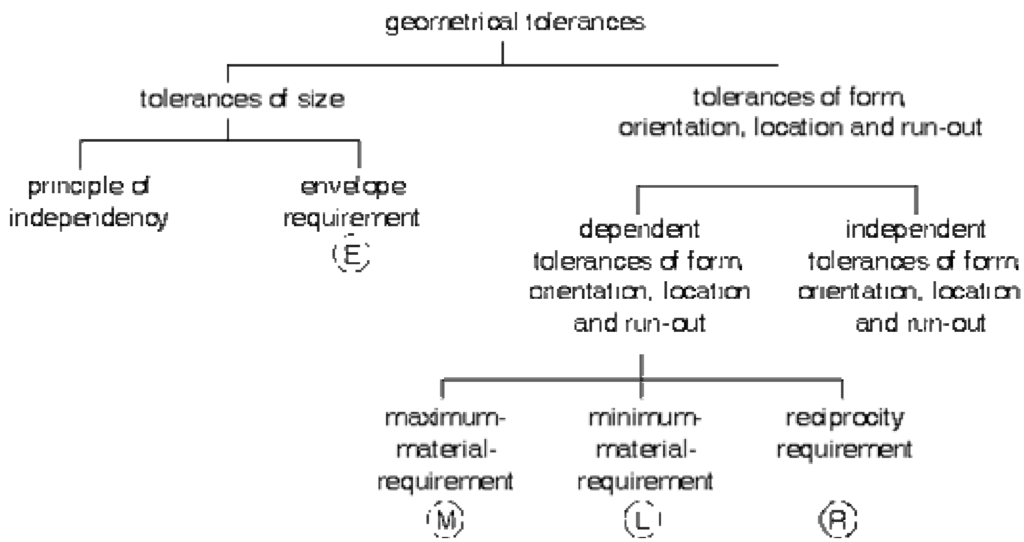


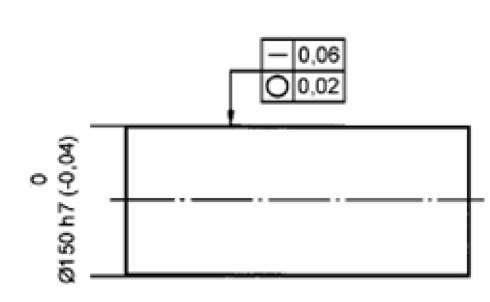
Figure 1. Principle of tolerancing for geometrical tolerances (ISO 1101) [1]

In describing different kinds of sizes, the mating of components was pointed out several times. Mating of components is one of the main reasons for tolerancing. Only by giving tolerances and calculating the relationship between all the geometrical features could interchangeable manufacture in its modern form be made possible. Due to the fact that different nations had different standards for tolerancing in use, different interpretations of one drawing were possible. The ISO published the standard ISO 8015 in 1985, which should harmonize the tolerancing. With the introduction of ISO 8015 a clear correlation between tolerancing deviations of form, location and those of size (mainly at cylindrical, flat and parallel mating surfaces) was defined.

2. PRINCIPLE OF INDEPENDENCY

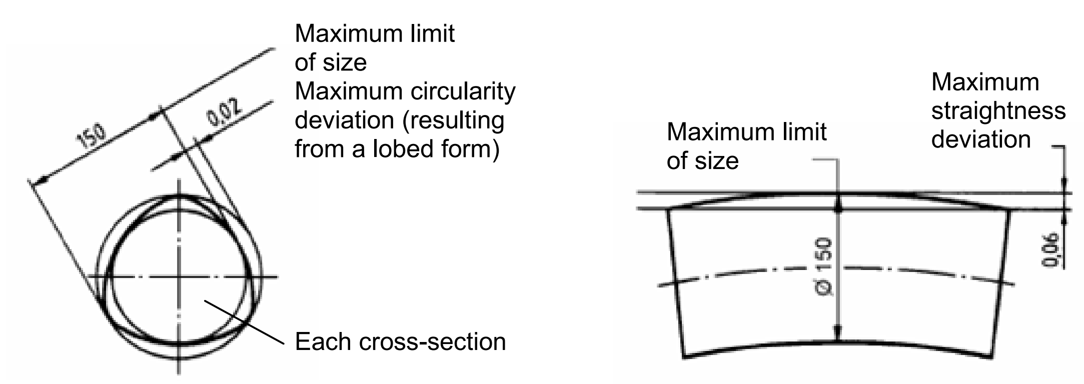
Each specified dimensional or geometrical requirement on a drawing shall be met independently of other requirements, unless a particular relationship is specified. This is the fundamental principle of tolerancing and it is named the “principle of independency” [3]. Therefore, where no relationship is specified, the geometrical tolerance applies regardless of feature size and the two requirements are treated as being unrelated. Consequently, if a particular relationship of size and form (see the envelope requirement), or size and location, or size and orientation is required, it shall be specified on the drawing.
When reference to the principle of independency is made on the drawing, the dimensional tolerance, regardless of whether it is expressed as a numerical tolerance or an ISO tolerance, does not control the form if the form deviation is such that it will not be detected by two-point measurement.
In conclusion, dimensional tolerances do not limit form deviations unless such a limitation is specified in the tolerance requirement:

a) A linear dimensional tolerance controls only the actual local sizes (evaluated by two-point measurement) of a feature (a cylindrical surface or two parallel plane surfaces), but not its form deviations (for example circularity and straightness deviations of a cylindrical feature or flatness deviations of two parallel flat surfaces.)
Form deviations shall, however, be controlled by the geometrical tolerances or envelope requirement.
There is no control of the geometrical interrelationship of individual features by the linear tolerances. For example, the perpendicularity of the sides of a cube is not controlled and, therefore, it requires a perpendicularity tolerance dictated by the function requirement.
b) An angular tolerance, specified in angular units, controls only the general orientation of lines or lines on surfaces, but not their form deviations. The general orientation of the line derived from the actual surface is the orientation of a contacting line of ideal geometrical form. The maximum distance between the contacting line and the actual line shall be the least possible value.
Form deviations are controlled through geometrical tolerances.
Geometrical tolerances are used to control form, orientation and/or position on real or abstract features, regardless of the feature size.
The geometrical tolerances will, therefore, apply independently of the actual local sizes of individual features. The geometrical deviations may be at a maximum whether or not the cross sections of the respective features are at maximum material size. For instance, a shaft with maximum material size at any cross-section may have a lobed form deviation within the circularity tolerance, and may also be bent by the amount of the straightness tolerance, see figures 2a and 2b [3].



Tolerancing principle ISO 8015

a)



b)

Figure 2. Principle of independency: a) Drawing indication; b) Interpretation [3]

If the principle of independency is used at a hole, checking involves proving that all local two point measurements are within the limits of size. Deviations of form and parallelism are not globally limited by the principle of independency, except for the barrel form, the saddle form, the cone form in axial section and the even-numbered polygons in a radial section (e.g. oviform). Further bends and uneven-numbered polygons (e.g. n lobed) are not limited. During the construction phase it is generally not obvious which deviations production might cause. This is why in certain cases geometrical tolerances have to be set out of functional reasons as well as tolerances of size.
The principle of independency should be used generally for features, which are not to be mated.
On the drawing the fundamental principle of tolerancing is be indicated by the note “Tolerancing principle ISO 8015". The note shall be placed above the title block.

3. ENVELOPE REQUIREMENT

The linear and geometrical tolerances are independent of each other, which mean that the geometric tolerances apply regardless of the feature size. The geometrical deviations may be at maximum whether or not the cross-sections of the respective features are at maximum material limit/size (the size of the smallest permissible hole or the size of the largest permissible shaft respectively). This is true unless a particular relationship has been specified. If there is a need for mutual dependency of size and geometry, the “envelope requirement” or the “maximum material principle” can be used [3].
The envelope requirement - on the drawing is noted with the symbol Ⓔ - establishes a relationship between size and form, and the maximum material principle - on the drawing is noted with the symbol Ⓜ - establishes a relationship between size and form, orientation or/and position (Fig.3)
So, the envelope requirement is based on the dependency between the form of a feature and its actual local size and it states that the real feature must not exceed the geometrical ideal envelope with the maximum material limit within the mating zone. The real size has to be as far away from the maximum material limit, as the expected deviation of form will be. In practice, the application of the envelope requirement means that if the actual size of the feature deviates from the maximum material limit, the form deviations are allowed to be larger.

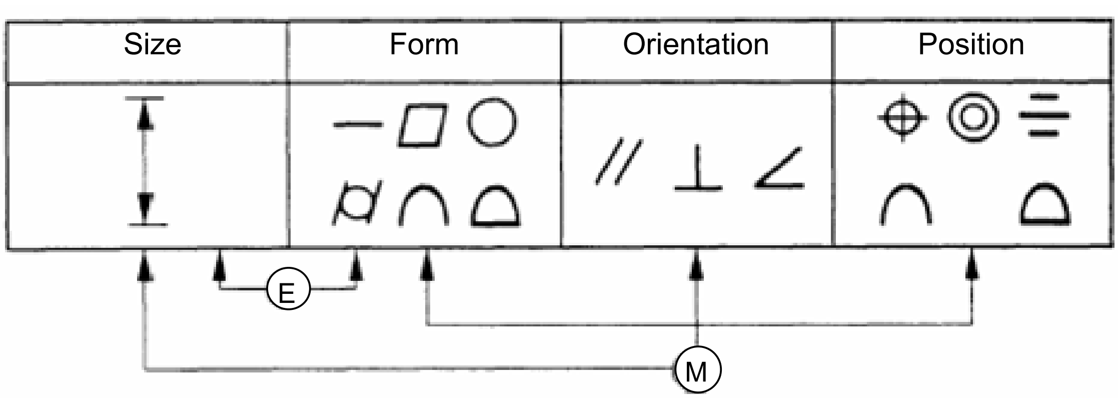


Figure 3. Application of the independence principle and the envelope requirement

The envelope requirement may be applied to a single feature, for instance a cylindrical surface or a feature established by two parallel flat surfaces. The envelope requirement is used for features which are to be mated.

The envelope requirement may be indicated either by the symbol Ⓔ placed after the linear tolerance (Fig. 4,a) or in relevant cases by reference to an appropriate standard which invokes the envelope requirement. This applies regardless of if the tolerance has been indicated as a numerical tolerance (with deviations) or by means of an ISO symbol.

Figure 4,a shows an example of the envelope requirement applied to a cylindrical feature. The function requirements are [3]:

- the surface of the cylindrical feature shall not extend beyond the envelope of perfect form at maximum material size of Ø150;
- no actual local size shall be less than Ø149,96.

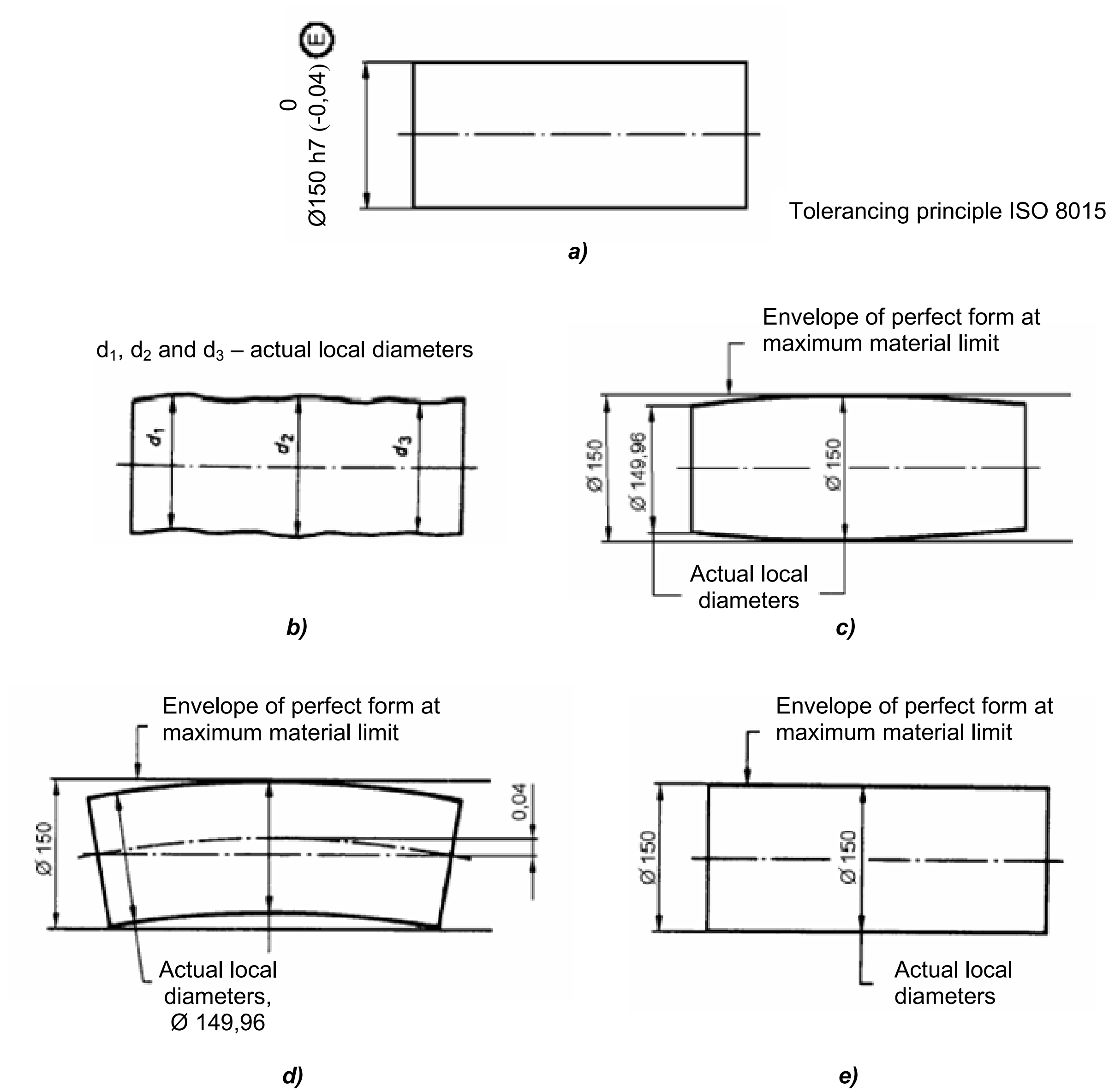


Figure 4. Envelope requirement: a) Drawing indication; b,c,d,e) Interpretation [3]

The drawing indication means that the actual part shall meet the following requirements:

- each actual local diameter of the shaft shall remain within the size tolerance of 0,04 and may therefore vary between Ø150 and Ø149,96, see figure 4,b;
- the entire shaft shall remain within the boundary of the envelope cylinder of perfect form of Ø150, see figures 4,c and 4,d.

Hence it follows that the shaft shall be exactly cylindrical when all actual local diameters are at the maximum material size of Ø150, see figure 4,e.

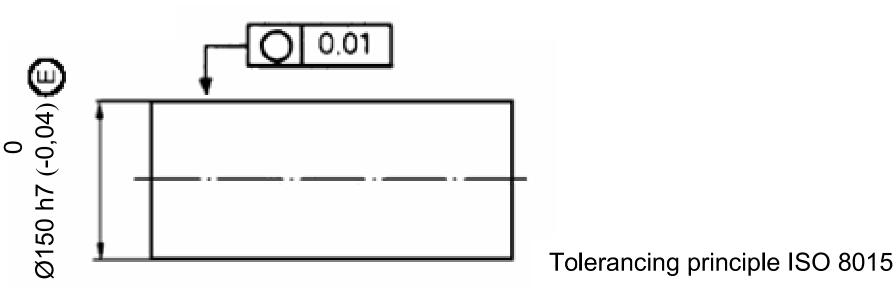
On the drawings where the principle of independency is not applied (the note “Tolerancing principle ISO 8015" is not indicated), it is applied the envelope requirement for all the dimensional and geometrical tolerance (the envelope requirement is not indicated). In this case, the tolerances are interpreted in the following ways within the prescribed length:

a) For holes: the diameter of the largest perfect imaginary cylinder which can be inscribed within the hole so that is just contacts the high points of the surface should not be smaller than the maximum material limit of size. The maximum diameter at any position in the hole must not exceed the least material limit of size.

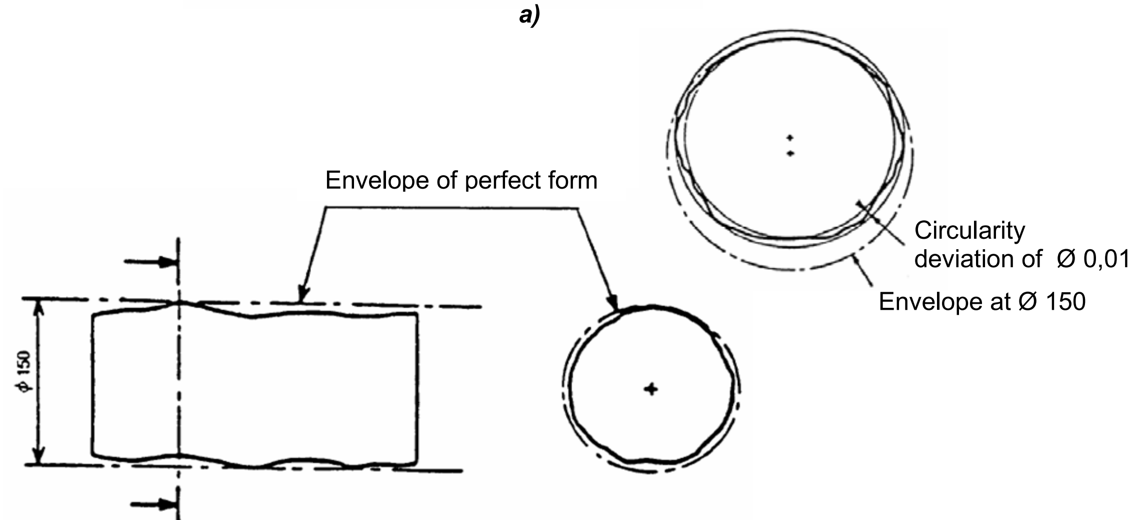
b) For shafts: the diameter of the smallest perfect imaginary cylinder which can be circumscribed about the shaft so that it just contacts the high points of the surface should not be larger than the maximum material limit of size. The minimum diameter at any position on the shaft must not be less than the least material limit of size.

The above interpretation means that if the part is everywhere at its maximum material limit, then the part should be perfectly round and straight, i.e. a perfect cylinder.

Unless otherwise specified and subject to the above requirements deviation from a perfect cylinder may reach the full value of the diametrical tolerance specified.



a)



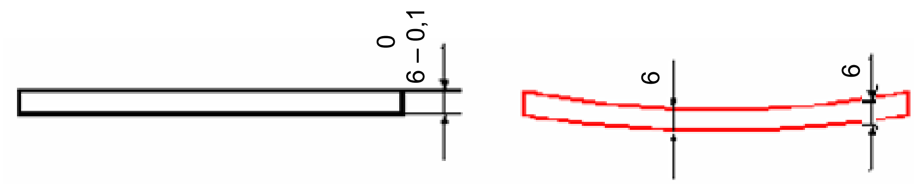
b)

Figure 5. Envelope requirement: a) Drawing indication; b) Interpretation

In special cases, the maximum form deviations permitted by the above interpretation may be too large to allow satisfactory functioning of the assembled parts. In such cases, separate tolerances shall be given for the form, e.g. separate tolerances on circularity and/or straightness (see fig.5). If we are adding on the previous example a complementary form exigency - circularity tolerance (Fig.5,a), that is a compulsory restriction in comparison with the dimensional tolerance, the interpretation in given in the figure 5,b.

4. APPLICATIONS

The effect of the principle of independency is shown as an example of a plate (Fig. 6, a, b). All two-point measurements are inside the tolerance zone of size. The deviation of flatness is therefore not crucial. In many cases this is completely sufficient because it is possible that there is no need for mating of the plate with another component. Deviations of form like flatness or straightness are given satisfactorily by general tolerances.

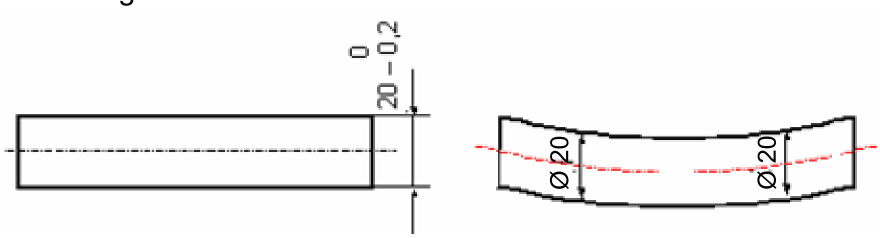


Tolerancing principle ISO 8015

a) *b)*

Figure 6. Application of independence principle on a plate: a) Drawing; b) Part to be accepted

In case of a shaft tolerancing of diameter does not affect straightness of the cylinder's axis (Fig. 7,a,b). This means, the shaft diameter is accepted as long as all local sizes are within the toleranced range.



Tolerancing principle ISO 8015

a) *b)*

Figure 7. Application of independence principle on a shaft: a) Drawing; b) Part to be accepted

The envelope requirement can be applied to a cylindrical surface or a feature established by two parallel plane surfaces. The effect of the envelope requirement is shown as an example of a shaft (Fig. 8,a,c). The requirement means that the envelope of perfect form at maximum material size of the feature shall not be violated, that is any form deviations need to be included within the limiting dimensions, i.e., the envelope requirement.
Ⓔ after the value of the diameter means that the form errors shall be within the dimensional tolerance. At maximum material limit (ø20 mm), the form errors must be 0.
So, if the shaft actual diameter in several cross-sections would deviate from its maximum material size (ø20 mm), within tolerance, it does not have to be perfectly straight or cylindrical as long as it fits into a ø20 cylinder with a perfect form (Fig.8,b). This means

that the shaft shall be exactly cylindrical when all actual diameters are at the maximum material size of ⌀20 (Fig.8,d).

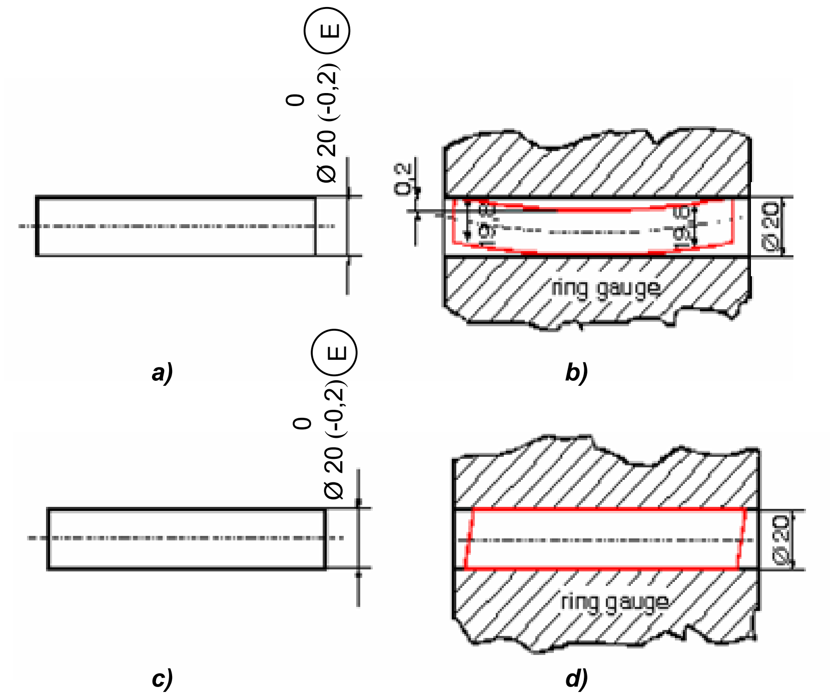


Figure 8. Application of envelope requirement on a shaft: a,c) Drawing; b,d) Part to be accepted

The envelope requirement limits only parallelism, not other tolerance such as perpendicularity, symmetry or coaxiality. So, by stating the envelope requirement, the actual allowed size deviation is decreased by deviations of form and parallelism of the component. The geometrical ideal envelope of maximum material limit must not be exceeded. If the envelope is not exceeded it is legal for the deviation of form to fulfill completely the tolerance of sizes. Full size tolerance zone may be spent for form deviations if the actual size meets the minimum material limit. The more the actual size deviates from maximum material limit the higher the corresponding deviation of form can be. There is one case in which utilization of the envelope requirement is senseless: if the deviation of form exceeds the tolerance of size. In this case envelope requirement is partially overruled by this property of form.

5. TOLERANCE INSPECTION

In order to check that a part is within the tolerances specified on the drawing, ISO has established special regulations for methods of inspection and measuring instruments. Parts may be inspected either by means of indicating measuring instruments or fixed limit gauges: plain limit gauges, limit indicating gauges. Some of the main factors which may influence the choice of inspection method are [6]:
- Plain limit gauges check both the size and the form of the part;
- Limit indicating gauges and indicating measuring instruments give the part size in the measuring position only and do not check the form of the part;
- Limit indicating gauges and indicating measuring instruments generally permit sampling inspection (by variables) which gives warning when the sizes approach the part limits during a continuous manufacturing process.

The basic principle of inspection is that the methods used for inspection shall accept only parts which lie within the specified limits of size and form.

When the envelope condition is required, the Taylor principle, that is full-form gauges, applies. The principle shall be interpreted in the following way [6]:

- The maximum material limit of a part shall be checked by means of a GO gauge of full form and made exactly to the maximum material limit of that part. The length of engagement of the GO gauge shall be the same as the surface specified on the drawing;
- The least material limit of a part (the size of the largest permissible hole or the size of the smallest permissible shaft respectively) shall be checked by means of a NOT GO gauge designed to check individually each actual local size of the part and made to the least material limit for that element.

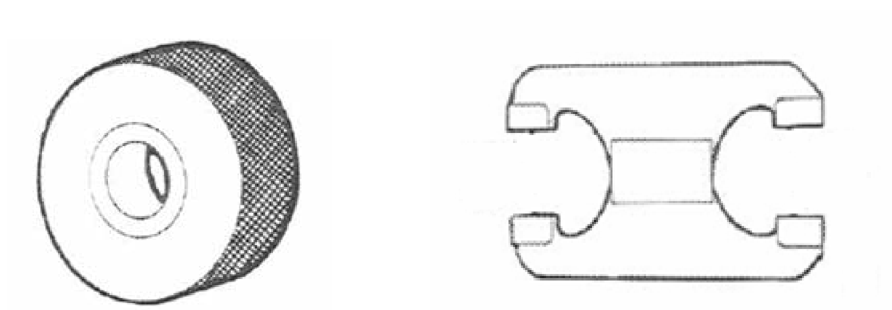
Strict application of the Taylor principle for cylindrical parts entails the following gauging procedure:

a) The maximum material limit of the part is checked with a plug gauge or ring gauge of perfect form with a length equal to the length of the part, or the length of engagement of the part to its mating part, and a diameter exactly equal to the maximum material limit of the part. This gauge should be able to fully pass into or over the part.

b) The least material limit of the part is checked with a gauge designed to contact the part at two diametrically opposite points separated by a distance exactly equal to the least material limit of the part. This gauge should not be able to pass into or over the part at any position.

For instance, a shaft made to ϕ 20 h7 $\left(^{0}_{-0,2}\right)$ Ⓔ shall be inspected for form as well as for size, with a plain limit gauge – ring gauge type (see Fig.9,a)

When the condition is not required, the local sizes only need to be measured or gauged. So, a shaft made to ϕ 20 h7 may be measured directly with two-point measurement using an indicating measuring instruments or checked with a gap limit gauge – snap gauge, (see Fig.9,b) because it is necessary to inspect only the actual local size.



a) *b)*

Figure 9. Ring gauge (a) and snap gauge (b)

6. CONCLUSION

The industrial practice uses the principle of independency already for a long time. The principle of independency states that each tolerance of size, form, orientation, location and run-out has to be met independently. This means for a toleranced dimension that all local actual sizes have to be within the limits of size. Checking by mating is not allowed.

The principle of independency is valid in general, however there are limiting conditions, like envelope requirement which relates to the different tolerances of a geometrical feature. The envelope requirement is based on the dependency between the form of a

feature and its actual local size and it states that the real feature must not exceed the geometrical ideal envelope with the maximum material limit within the mating zone.
Theoretically, applying envelope requirement in a lot of cases checking according to Taylor´s principle would have been necessary. In fact mostly measuring checking (e.g. by calliper) is done which only can take local actual sizes at the geometrical features of a part. Tolerancing of fitted components can be simplified using the envelope requirement.
Following the principle that a drawing should describe the part functionally in order to reduce manufacturing and checking costs, all companies had to convert to the principle of independency on long term.

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