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Procedia CIRP 75 (2018) 179–184

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15th CIRP Conference on Computer Aided Tolerancing – CIRP CAT 2018

On the usage of Least Material Requirement for Functional Tolerancing

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Abstract

ISO 2692 core concepts: Maximum Material Requirement (MMR) and Least Material Requirement (LMR) are well established for functional tolerancing and are used to guarantee assemblability, extremal values of clearance and minimum wall thickness. The LMR has not been extensively investigated in research and still not enough considered in industrial practices. In this paper, LMR's capability to devise requirements on assemblies with clearance is shown, and the conformity assessment, in dimensional metrology, based on Least Material Virtual Size is presented. A case study demonstrates the effectiveness of this work. New insights for virtual size representation within tolerance zone are also discussed.

Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.

Keywords: Functional Tolerancing; Least Material Requirement; Assembly

1. Introduction

Functional tolerancing (or tolerancing for function) addresses the issues of the mapping of functional requirements into geometrical specifications completely described by and in conformance with actual ISO GPS (Geometrical Product Specifications) and ASME Y14.5 tolerancing standards.

The functional requirements are in general represented by geometric constraints that limit the size, the shape, the orientation and the location between surfaces and define their relative displacements. ISO application standards provide the designers with a graphical language to specify toleranced features and datums and to define the tolerance types and use tolerance symbols. The current standards address the specification by dimension, the specification by zone and the specification by gauge (virtual boundary).

Specifications by gauge allow a function-oriented approach for assembly and permit the use of virtual boundaries in tolerancing. Virtual boundaries (maximum material and least material) were developed as the basis of a geometric model for CAD and Tolerancing proposed by Requicha [1] and Tolerancing for Function [2,3]. Furthermore, tolerance synthesis approaches have been developed by several researchers using virtual boundaries to enable the expression of the condition corresponding to assembly and function. Dantan et al. [4] developed the concept of gauges with internal mobilities to limit the geometrical variations of parts. The Maximum Material and the Least Material Requirements are verified by the use of virtual gauges with internal mobilities [5]. A conceptual model of "virtual fitting gauges" [6,7] exploiting the maximum and least material requirements have been developed by Pairel et al. and algorithms were implemented for dimensional metrology applications [8,9]. Anselmetti uses these principles for functional tolerancing in assembly and for 3D tolerance stack-up [10].

ASME Y14.5 [11] and ISO 2692 [12] standards detail the principles of maximum and least material requirements. Moreover, inspection tasks using physical gauges and virtual (digital) gauges refer to these standards based on the ability of a geometric feature (or a set of geometric features) to mate with a counterpart with a theoretically exact shape and dimension defined by specifications.

In this paper, the usage of maximum material requirement (MMR) and least material requirement (LMR) for functional tolerancing and specifically in the context of tolerancing for assembly is examined.

In section 2, the role of MMR to ensure assembly is depicted. LMR has not been extensively investigated in

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10.1016/j.procir.2018.04.068

research and still not enough considered in industrial practices. In section 3, LMR's capability to devise requirements on assemblies with clearance is shown, and the conformity assessment, in dimensional metrology is presented in section 4. A case study demonstrates the effectiveness of this work and new insights for virtual size representation within tolerance zone are also presented.

2. Material Requirement and Functional Tolerancing

2.1. Introduction

The maximum material requirement (MMR) and least material requirement (LMR) as defined in ISO 2692 are nowadays well established for functional tolerancing and are used to guarantee assemblability, extremal values of clearance, assembly accuracy and minimum wall thickness. They are indicated in technical drawings by Material Modifiers symbols Ⓜ and Ⓛ and refer to integral geometric elements from features of size.

When the MMR (LMR) is specified, the two requirements – size and geometrical tolerance – are combined into one collective requirement. The actual surface of the tolerance feature shall not violate the Maximum (Least) Material Condition state i.e. envelope defined respectively to the MMR (LMR) specification. The dimension defining the MMC or LMC of a feature is denoted MMS (Maximum Material Size) or LMS (Least Material Size).

The created ideal geometric elements which form a nominal model of a gauge are denoted as maximum material virtual condition (MMVC) or least material virtual condition (LMVC). The size of a geometric element of the gauge is referred to as maximum material virtual size (MMVS) or least material virtual size (LMVS).

The following rules are applied for the determination of the parameters required for the characterization of MMVS and LMVS:

- For external features of size the envelope size (MMVS) is equal to the sum of maximum material size (MMS) and the geometrical tolerance, whereas for internal features of size, it is equal MMS minus the geometrical tolerance.

- For external features of size the envelope size (LMVS) is equal to the least material size (LMS) minus the geometrical tolerance, whereas for internal features of size, it is equal to the sum of LMS and the geometrical tolerance.

2.2. Simplification and new writing rules

As stated in the previous section, the current ISO 2692:2014 standard provides the rules for the computation of the size of a geometric element of the gauge based on the combined effect of the size and the geometric tolerance with material modifiers. It becomes more complex when dealing with datum. Moreover, the verification of local dimensions is unnecessary in general.

A new writing has been proposed in [13] (fig.1 and fig. 2) and permits to simplify the virtual (envelope) size computation by directly reporting the value of the virtual size in the second compartment of the tolerance frame (tolerance zone indications) and near each datum. This idea had been already depicted in the ASME Y14.5:2009 standard for datum (section 4.11.6.3).

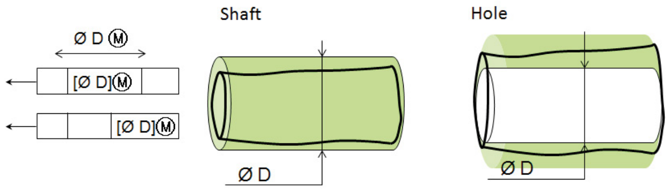

Fig. 1. Maximum Material Requirement for a cylinder

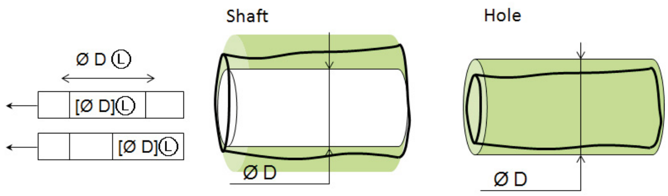

Fig. 2. Least Material Requirement for a cylinder

2.3. Functional Tolerancing using CLIC method

The CLIC method (French acronym for "Localization with Influence of Contacts") [14] enables functional tolerancing on the basis of virtual boundaries and benefits from explicit rules to derive geometric specifications from the junctions between parts according to their priority order (primary, secondary and tertiary links) using positioning tables.

The CLIC method defines one main datum system related to set-up surfaces of the considered part and one auxiliary datum system to locate each other contacting part. Based on this, and a table-based specification rules, each geometrical feature has a defined tolerance specification schema. These geometrical specifications guarantee the assemblability of the parts or blocks in pairs and the positioning quality according to the preponderance of the contacts defined in the positioning tables.

2.4. Ensuring assembly using the MMR

To illustrate this approach, a case study of a mechanism consisting of 3 parts is considered here. In fig. 3, the primary junction is highlighted in red, the secondary junction in green and the tertiary junction in blue. The maintaining surfaces, which do not ensure positioning, are highlighted in yellow. It is important to note that there are junctions with clearance and fits with interference. Here, the cover is mounted with clearance on the body, and each pin is fitted in the body. The body/pins set is mounted with clearance in the housing.

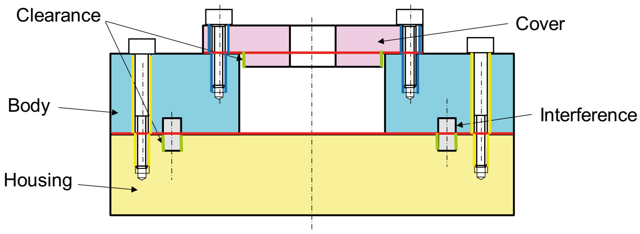

Fig. 3. Junction between parts

Fig. 4 provides the specifications for assembling the cover and the body. Flatness (1) on each primary plane ensures the quality of the contact and avoids the deformations of the parts during the tightening of the screws.

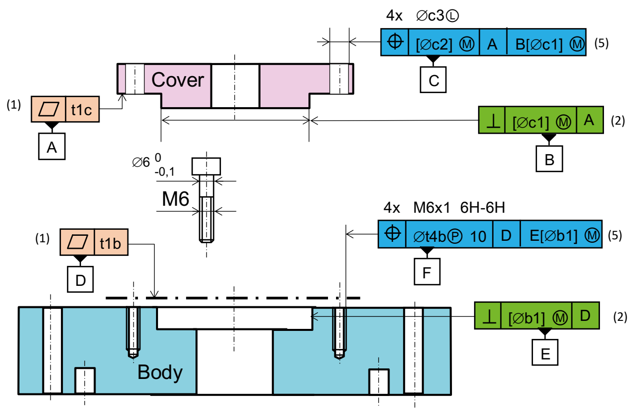

Fig. 4. Junction between the cover and the body

The secondary junction between the cover and the body is enabled by two cylinders B and E with clearance. The mountability is ensured by imposing perpendicularity (2) with MMR. The boundaries shall not to be exceeded by each part. The dimensions of the boundaries b1 and c1 satisfy the following condition: b1-c1 is equal to minimum clearance.

The tertiary junction between the cover and the body is enabled by four screws. The screws are tightened in threads F. The cover is positioned by four bores C with clearance. For the cover, a location (5) with MMR, enables enough space for the mountability of the screws. The datum B is also specified with MMR, because the clearance between B and E allows the floating of the assembly to facilitate the mounting of the screws. For the body, a location (5) of the axes of the threads F in the projected zone Ⓟ limits the space occupied by the screws. The value of 10 mm represents the thickness of the cover. The most unfavourable case is obtained when the bodies of the screws are at the maximum of material.

Fig. 5 shows the specifications ensuring the assembly between the body and the housing. Primary features impose the flatness (3) of each plane to ensure the quality of the contact and to avoid the deformations of the parts during the tightening of the screws.

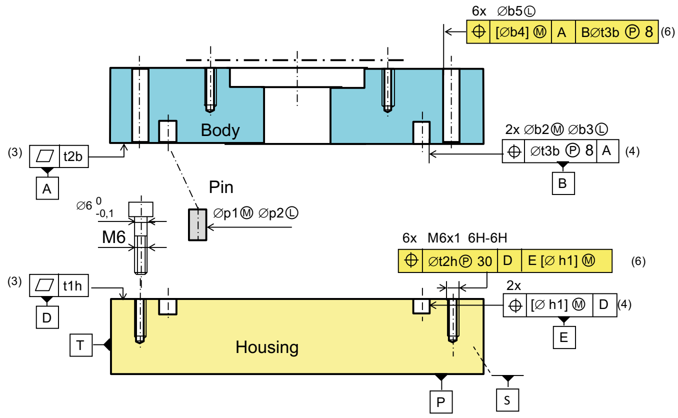

Fig. 5. Junction between the body and the housing

Two pins provide the secondary junction between the body and the housing. The pins are tightened in two bores B of the body. The subset formed by the body and the two pins is positioned with clearance in two bores E of the housing. The assembly is ensured by imposing that a boundary has not to be exceeded between the pins and the bores E. For the body, the clearance between the pins and the housing is favourable to the mountability. For the housing, a location (4) on the bores E with MMR let a free space ∅ h1. For the body, a location (4) for B in the projected zone Ⓟ of value of 8 mm represents the outer part of the pins. The worst case for the mountability is obtained when the pins are at the maximum material ∅p1.

The set of six screws maintain the two parts in position. The clearance between the holes E of the housing and the pins allows the sliding of the body to facilitate the assembly of the screws. For the body, a location (6) requires MMR, because the clearance is favorable to the mountability of the screws. The datum B is therefore defined with the tolerance zone Ø t3 Ⓟ. The value t3 corresponds exactly to the tolerance zone of location (4). Each axis of B can float inside two cylinders of diameter t3. This datum system is equivalent to a datum defined by two pins of diameter p1 temporary centred in the two holes (B) and with a tolerance zone of diameter t3+p1 at MMR.

In location (6) of the axes of the threads of the housing, the projected zone Ⓟ of 30 mm represents the thickness of the body. The most unfavourable case occurs when the bodies of the screws are at the MMVS of Ø6. The required area for the screws is of value of 6+t2h must respect the free space Øb4 allowed by location (6) of the body. The mobility allowed by the clearance only facilitates this assembly.

3. Least Material Requirement for Functional Tolerancing

3.1. Functional requirement expression

The example in fig. 6 illustrates the requirement of the position of the bore H of the cover with regard to the datum system P|S|T of the housing: the bore H has to be outside a cylinder of diameter ØX.

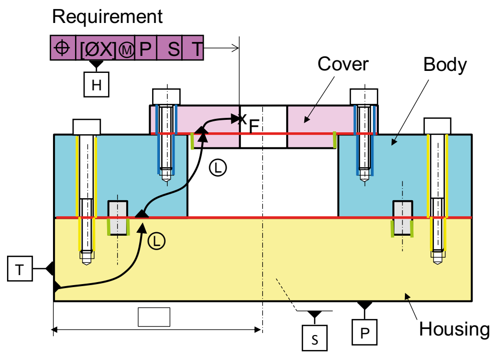

Fig. 6. Functional requirement expression

Mathematically, this requirement can be expressed as follows: the point F on the bore H does not have to overtake the cylinder ØX centred on the nominal position with regard to P|S|T, whatever the position of the body and the position of the cover allowed by the clearances.

3.2. Specification using the LMR

The previous requirement depends on three links of the tolerance stack-up and the clearances in both junctions (Fig. 6).

To enable the transfer of this functional requirement, it is necessary to locate every influential junction with regard to the main reference system. Since the clearances are often unfavourable, the toleranced features and the datum are specified with the modifier Ⓛ corresponding to the Least Material Requirement.

The end part (cover) contains the functional surface specified by the requirement. On the cover, the specification (7) is defined by duplicating the specification schema of the requirement and by imposing the new main datum system which is noted here A|B|C with the modifier Ⓛ for all the datums with clearance. In this simple case, the datum C is not useful because the bore H is centred on B, see Fig. 7.

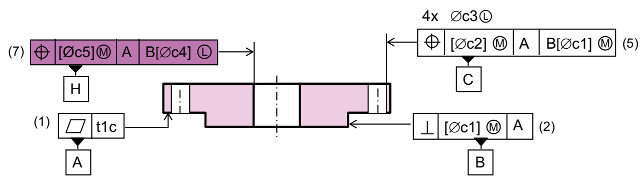

Fig. 7. Tolerancing of the cover

Both specifications (5) and (7) impose respectively the limits at the maximum and at the least material for the cylinder B. The difference c1 - c4 is thus the manufacturing tolerance of B. To reduce the costs, it is necessary to maximize this tolerance.

The body is an intermediate part of the tolerance chain. For an intermediate part, the specification (8) locates the junction with the cover with regard to the junction with the housing (see Fig. 8). The modifier Ⓛ is placed on all the datums with clearance, because the clearances are unfavourable.

Both specifications (2) and (8) impose respectively tolerance zones at the maximum and at the least material for the cylinder E. The difference b6 - b1 is thus the manufacturing tolerance of E. It is necessary to note that these tolerances are expressed in different datum systems and include position and orientation deviations. To reduce the cost, it is necessary to maximize these tolerances.

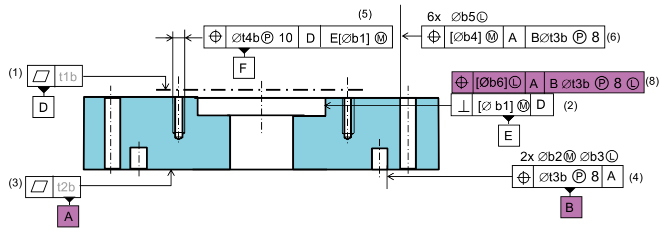

Fig. 8. Tolerancing of the body

The housing is an end part, which carries the datum system of the requirement. In this case, the specification (9) locates the junction with the body with regard to the datum system of the requirement, which is simply duplicated. The modifier Ⓛ is placed on specified surfaces, because the clearances on holes E are unfavourable.

Both specifications (6) and (9) impose respectively tolerance zones at the maximum and at the least material for the cylinder E (fig. 9).

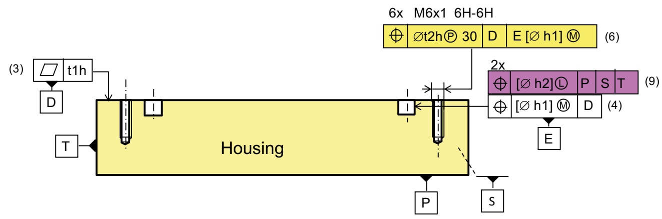

Fig. 9. Tolerancing of the housing

3.3. 3D tolerance stack-up

The tolerance chain considered here corresponds to the functional requirement of Fig 6. It is simply obtained by considering the virtual parts with junctions at the least material and pins at least material (Fig. 10). The limit X must be respected for all the positions of parts allowed by the clearances.

If all the junctions were perfectly centred, the cylinder H would respect the tolerance zone of diameter c3. With the clearance, this bore H is mobile.

In this simple example, the bore H is centered on both junctions. The maximal displacement of the bore is simply equal to the clearance (fig. 10). The free space is thus reduced. For this requirement, the relation to be respected is:

$$c5 - (b6-c4) - (h2-p2) \geq X$$

Thus, this approach enables to consider successively all the functional requirements of the assembly to ensure that all the conditions are respected.

The set of all the established relations allows to optimize all the unknowns b1, b2, ... and tolerances.

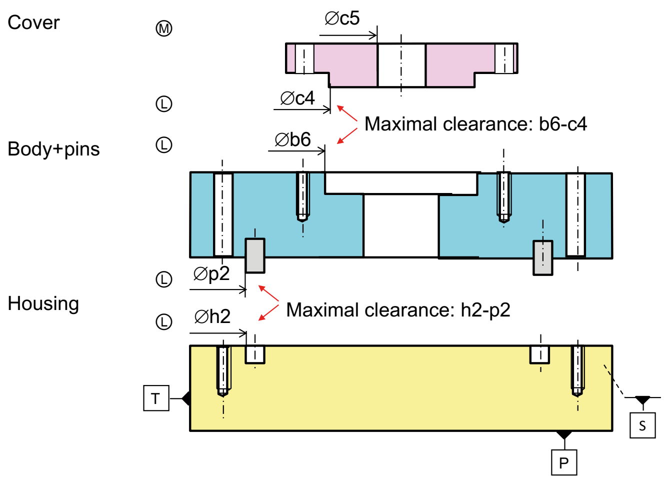

Fig.10. Model for tolerance chain

4. Inspection and Gauging of Least Material Requirement

A specific measurement method is required for inspection of specification with Least Material Requirement on datum system. The ISO 2692 does not provide conformity criteria. In fact, the actual part must be compared to a virtual part corresponding to LMVS.

Prior to the extensive use of Coordinate Measuring Machines (CMM) in industry, hard or physical gauges (also called functional gauges) play an important role for the inspection of products. Based on the fundamental Taylor principle, the used artefacts satisfy the go or no-go gauging which mimics the material requirement and virtual boundaries.

Despite its popularity, verification by gauging gives only a binary result. This inspection approach does not provide any quantitative information about the current value of the tolerance and if the part is rejected, it is almost not possible to know if it is due to the size, position, orientation or any combination of these [15].

This inspection by means of physical gauges apply to toleranced and datum features and hence not limited to single geometrical features. It can also address set or patterns of geometrical features. However, specific functional gauges need to be manufactured and calibrated and are not systematically reused which may involve very expensive costs.

Moreover, the consideration of both toleranced features and datum features with maximum material requirement or/and least material requirement is an important challenge for dimensional metrology.

In the case of the location (7) of the cover in figure 7, the functional gauge is defined from the two cylindrical features of perfect shape having a MMVS of value c5 and a LMVS of value c4 (fig. 11).

The inspection of such specification can be realized with an additional inspection part holder consisting of a cylindrical feature of perfect shape having a nominal diameter c greater or equal to the MMVS. The case of c equal to MMVS simultaneously enables the control of the perpendicularity specification.

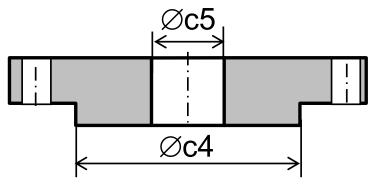

Fig.11. Functional Gauge of the cover

A set of dial gauges fixed on the part holder are placed on the specified surface H of the gauge. (figure 12) Each dial is set to zero for the maximal displacement of gauge in corresponding direction. This limit must be respected by each real part whatever its position in part holder.

The smallest indication defines the margin on the specification which can be an interesting quantitative value.

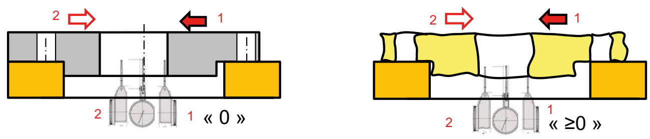

Fig.12. Inspection of the cover

This validation criterion actually combines the effect of the toleranced feature and the datum feature B as well as the part's contribution to the clearance in the assembly. It is not required that the datum B respect the boundary ∅c4 if the specified surface is well centred. In the same way, the bore H can exceed the c5 limit if the floating in B is small.

The inspection using CMM requires the implementation of virtual gauges and virtual part holder within CMM software. For each extracted point of hole H, the maximal displacement of the virtual gauge is compared to the maximal displacement of the real part in the normal direction to the surface on this point.

5. Conclusions

Specifications based on Maximum Material Requirement (MMR) and Least Material Requirement (LMR) in tolerancing and assembly allow a function-oriented approach for assembly and the practical use of virtual boundaries in tolerancing and thus contribute to functional tolerancing.

In this paper, the role of MMR to ensure assembly is highlighted and LMR’s capability to devise requirements on assemblies with clearance is shown in a simple assembly. Based on the actual standards and their evolution, material modifiers are becoming very well adapted to the expression of functional requirements while enlarging the tolerances and allowing a more consistent verification in dimensional metrology by gauging or CMM based inspection. The consideration of LMR on datum allows an important benefit since it enables accepting parts by the compensation of the different deviations permitted by tolerance zones and clearances.

New insights for virtual size representation within tolerance zone are also presented in this paper and have been recently proposed in the new revision of ISO 2692 (ISO/WD 2692:2018).

Future work will focus on the characterization of the tolerance zone in case of the projected tolerance zone Ⓟ, and the newly Least Square (Gaussian) Feature Ⓖ, combined with LMR to develop a more comprehensive usage for assembly applications.

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