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The geometrical specification in concurrent product design

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Abstract

In this paper, in the first place an analysis on the usual practices for the specification of acceptable geometrical variability in functional geometrical features of parts is carried out, and an interpretation on the 'geometrical variability specification' concept as introduced by ISO standards is established. In the second place, a wider and more integrative proposal for geometric specification is made, conceived as a concurrent process inside the product design and development process itself, where all problems referring to tolerancing-related information handling along the product life cycle are dealt with.

1 Tolerancing in the process of design for product development

Along the process of designing new or improved products, both the geometrical elements that interrelate the parts to achieve the pretended functional conditions of a mechanism, and those other geometrical elements which the assembly conditions among the parts to be fitted depend on, must be subject to specification of the admissible geometrical variability range, within which the functional and/or assembly conditions can still be considered as acceptable.

Until the last decade of the 20th Century, the priority objective for organizations was to put into the market competitive products regarding their technological features and their price. Later, new decisive factors for the products' competitive level appeared, as the reduction of the necessary time to put a new product into the market (time-to-market), the incorporation of the product use requirements in the design stage, the need to provide easy component interchangeability along maintenance operations, product reliability, and product quality.

The feasibility of incorporating to the product all or some of the above mentioned factors depends strongly on the company having implemented an appropriate method for managing the admissible geometrical variability along its design and development processes.

In order to achieve an adequate management of the product geometric variability, it is considered that a set of factors must be taken into account, which will be analysed along this paper, such as: the usual practices for tolerance management during the company's design, manufacturing and inspection processes, the knowledge level and degree of application of the ISO standards for geometrical product specification, or the more or less integrated way used by each organization to plan and structure its products. By interacting among themselves, all these factors give rise to different results in the actual variability of the manufactured products, and as a consequence in their homogeneity and reliability.

2 The traditional approach to tolerancing

In the common practice of mechanical engineering, decisions on product tolerancing are made along the design process, focused fundamentally in achieving optimal functional conditions. Once all admissible dimensional and geometrical tolerances are specified on the part drawings, in the next stage the manufacturing engineering department defines the manufacturing processes and the necessary inspection methods in order to get products that are in accordance with the specifications from the drawings defining such a part, and the control engineering department defines the resources and systems to be used to check the control status of the manufacturing process at all times.

The former framework corresponds to a way of performing design and development of new products known as "sequential engineering", which is characterized by consisting of a series of stages organized in such a way that each of them doesn't start until the former one is completed.

The use of the sequential model involves that the times for putting into the market new products grow longer, because every change that is required by limitations in later stages to design has an impact on the first stages, forcing sometimes the company to change already launched supply orders for manufacturing or inspection equipment, thus paralyzing the development of later stages, and as a consequence of the mentioned changes the final product cost increases.

Once it has been shown the importance of having information about the later stages in the initial stages of the product design and development process, with the aim of incorporating improvements along the design process itself, several analysis techniques and tools have been developed, oriented to achieving more robust designs that incorporate along the design process the limitations and necessities of the later activities to be carried out, but without involving the rest of the functions.

Using those techniques and tools the number of changes and the cost are reduced, but their use also requests from the designer a better knowledge of the later development processes. This is an orientation defined by Yazdani [1] as the *product-oriented sequential design model*, which increases the level of confidence on the data generated along the design process, while keeping a sequential organization for the activities.

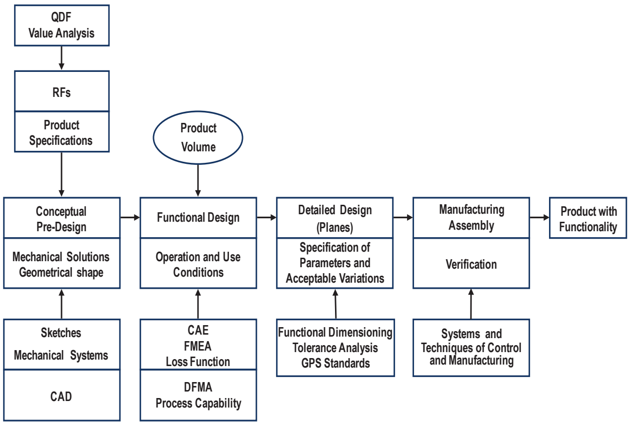

Fig. 1 Tools for improving quality in the product-oriented sequential design model.

As shown in fig. 1, this product-oriented sequential model incorporates analysis tools such as Design for Manufacturing (DFM), Design for Assembly (DFA), Taguchi Loss Function, etc., that don`t avoid the necessity of performing the subsequent revisions and adjustments after the retro-alimentation of information coming from the manufacturing, quality, ... processes, but get to reduce them on a high percentage. Tolerance allocation carried out using a sequential model can give way in some cases to tolerances that are unattainable with the available manufacturing processes –their capability doesn't make possible to obtain such tight tolerances–, or in other cases to very expensive tolerances –when in the tolerance allocation their cost is not considered–, forcing to perform later revisions and adjustments once the information retro-alimentation coming from the manufacturing and quality control is carried out.

3 Geometrical variability in the current ISO standards framework

The specifications applied to the part detailed drawings must express without ambiguities what are the target functional requirements, as otherwise there is a possibility of either parts being accepted that are not functionally valid, or of parts being rejected that are valid for the target functional requirements, as happens in the examples shown in figs. 2 and 3.

Thus, in the case study shown in fig. 2 there is only a dimensional tolerance specification for a rotating shaft. In case there were roundness defaults in the shaft's supporting journals as shown in the figure, hardly the pursued functional requirements would be achieved, even if all part measures are conform to the specified tolerance, as the discontinuous contact between the shaft and the bearing would result in a quick wear in its surface, causing performance losses, vibrations and noise.

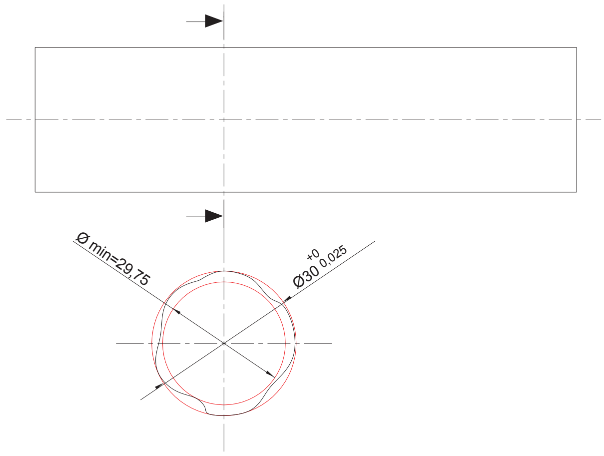

Fig. 2 Geometric specification of a shaft using only dimensional tolerances.

The case study of fig. 3 shows a situation in which truly valid parts for the pursued functional conditions could get rejected. The Φ10 hole is subject both to a dimensional tolerance and to a position geometric tolerance, that together with the pin dimensional tolerance must guarantee that the mínimum gap measure value ***H*** is between a lower value of:

20 - (5,010 + 0,005) = 14,985 mm

and a higher value of:

(20 + 0,010 + 0,005 - 4,992) = 15,023 mm

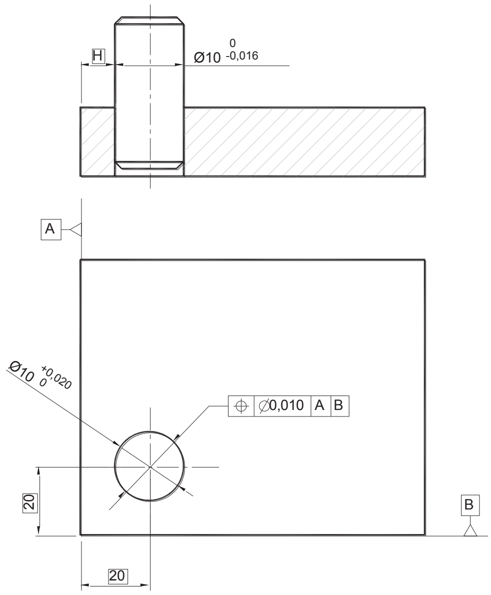

Fig. 3 Geometric specification of a functional condition.

The analysis of the case study shown in fig. 3 shows that a pin with an actual minimum diameter measure of 9,980 mm could get rejected when it must be assembled with a part which its hole maximum diameter measure is 10,010 mm and the maximum position deviation for such hole is 0,006 mm. In this circunstances for the gap measure value ***H***:

min H = 20 - (5,005 + 0,003) = 14,992mm

max H = 20 + (0,003 + 0,005 – 4,990) = 15,018 mm

Consequently, there could be a case where parts that are non-conform to specification but that are able to achieve the pursued functionality could be assembled.

These cases should be considered in the product technical documentation of the specified product.

The same analysis could be performed in cases where the dimensional tolerance or the position tolerance of the hole are outside the specified tolerance.

In order to make available to designers a tool for geometric product specification allowing to express without ambiguity the design intent, and at the same time to be able to reproduce it when defining the inspection method for such geometric feature, ISO published in 1995 the Technical Report ISO/TR 14638 [2], which constituted the starting point for a new generation of GPS (Geometrical Product Specification) standards. Those standards derive from the previous ones, but provide a more complete and current language of symbols, containing "by default" definitions and procedures to build specifications that allow univocal interpretations in all engineering stages involved in the product design and development along its life cycle.

Univocal interpretations will be reached if the same model is used in all scopes to define the tolerance zone corresponding to a certain specification. A conclusion of the analysis carried out on this subject by the authors [3], was that the definition of the tolerance zone performed using the elemental operations needed to conceive such specification as a theoretical inspection procedure, in the way it can be obtained from the current ISO standards framework, results in a smaller specification uncertainty. Thus, the knowledge and application of such framework becomes fundamental as a unifying way for the exchange of technical documentation.

Therefore, one of the objectives for the new GPS standards is to reduce the most the specification uncertainty. Sometimes companies are aware of having issues with their products, but don't realize that different interpretations for the same target functional requirement could exist due to ambiguity in tolerance specification on drawings. The problem increases when one or some of the parts are manufactured by a supplier, and so the drawing becomes a contractual element between both parties, that can be the subject of different interpretations by each party.

With the new GPS language product quality is improved, as when more precise information is available on the specified requirement, more right decisions can be made on the manufacturing process and inspection methods, achieving as a consequence more homogeneous parts that fit better the target functionality corresponding to such specification. Bennich and Nielsen [4] pointed out that, by implementing GPS standards in the company, a new specification tool to reduce uncertainty is made available, allowing to increase the admissible variability range of each specified feature. As the achievement of a tolerance involves a certain cost, by increasing such tolerance the manufacturing costs can be reduced. The mentioned authors estimate that reduction to reach 15%.

In the **ISO/TS 17450-2:2002** standard [5] a series of terms regarding operations with geometric elements are defined, among which some are worth to be mentioned: *"specification operation"* (an operation formulated either using only geometric expressions or mathematical algorithms, with the aim of performing product requirement specification, as a part of an specification operator), *"specification operator"* (an ordered set of specification operations, the result of a complete interpretation of the combination of all the GPS specifications from the product technical documentation), *"GPS specification element"* (a group of one or more graphic symbols that control an ordered set of one or more basic specification operations, defined by default, with which nominal elements, associated or derived, are obtained), and *"GPS specification"* (set of specification elements that together control an specification operation, having or not modifiers).

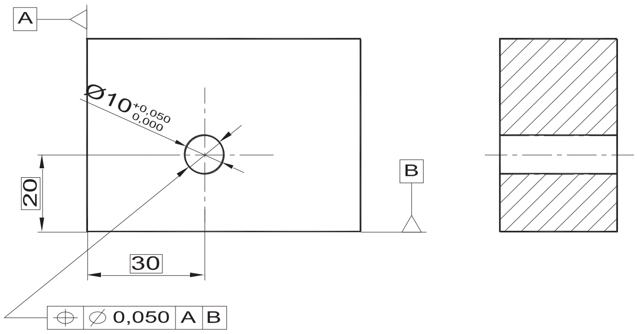

Fig. 4 Specification of a position geometrical tolerance for the axis of a circular hole.

In order to get things clear on the mentioned issues regarding the meaning of GPS specifications, an interpretation of the meaning of a specification for the position tolerance of a hole with respect to two reference planes A and B (fig. 4) is done following. It has been assumed in it that the only interest is in the hole location, as in order to control its orientation it would be necessary to incorporate a third reference element.

The meaning of the position specification operator is a consequence of the joint interpretation of a group of GPS symbols and standards; a description of the group's relation with such specification follows:

ISO 5459:1981 [6]: defines the criteria to establish references on actual part elements. A plane, a straight line, cylinder's axis, etc. can be used as references.

ISO 1101: 2004 [7]: contains the symbols to be used in order to indicate the geometrical characteristics that can be object of specification, and other complementary symbols such as the framed dimensions, the symbols characterizing the reference elements, the different kinds of tolerance rectangles to be used, etc.

ISO 5458:1998 [8]: defines the basic principles for position tolerances: their association to theoretically-exact dimensions, its application to determining the position of actual elements with regard to either other elements, or with regard to references (as shown in fig. 4), the tolerance area splitting symmetrically with regard to the theoretically exact position, etc.

ISO/TS 17450-1:2005 [9]: defines the specification operations that can be performed with the geometrical elements. For the part in the case study shown in fig. 4, the following operations must be applied to the actual part (1) shown in fig. 5:

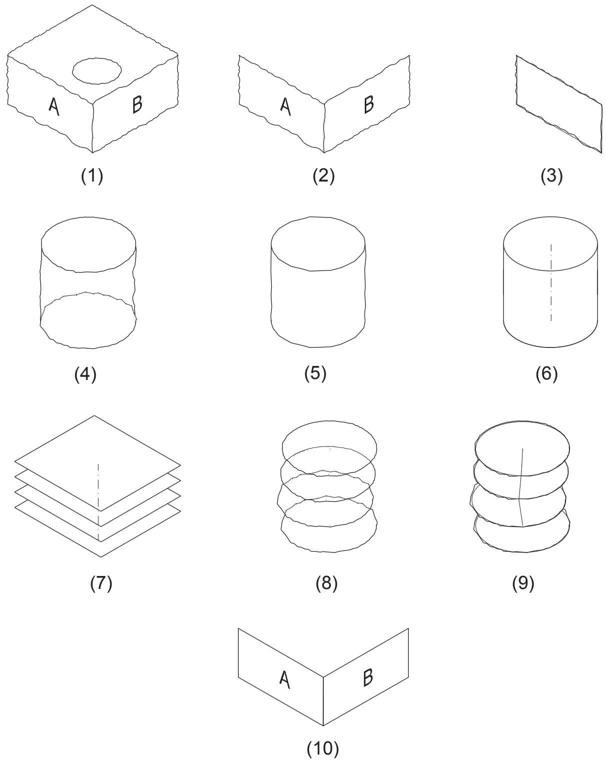

Fig. 5 Specification operations for building the position tolerance of a hole's axis.

(2) *"Partition"* of the non-ideal surface (A) specified as a reference.

(3) *"Association"* of an ideal plane to the actual surface (A). The association criteria defined by default in the ISO standards can be applied, or any other that is convenient (for instance, the tangent plane on the outer side of the material, placed at the less possible distance of point placed the most far away from the actual surface).

Steps (2) and (3) must be repeated for the other reference plane (B).

4) *"Partition"* of the cylindrical hole, separating it from the rest of the part using its limits, and *"extraction"* of a finite number of points from the actual surface of the hole by means of one of the strategies defined by the **ISO 12180-2:2003** standard [10], or any other strategy that could be convenient in the particular case being dealt with.

(5) *"Filtering"* of the points from the extracted cylinder, with the specified criterion, thus obtaining the cylinder representative of the actual surface of the hole.

(6) *"Association"* of an ideal cylinder to the non-ideal element resultant from the former filtering. The association criterion must be specified, unless the one defined by default by the standards is applied. The axis derived from the associated cylinder will have to be obtained.

(7) *"Construction"* of a set of ideal planes, perpendicular to the axis derived from the associated cylinder.

(8) *"Partition"* on the non-ideal circles determined by the intersection from each of the former perpendicular planes (7) with the filtered cylinder obtained in (5).

(9) *"Association"* of ideal circles to the non-ideal circles that have been obtained. According to **ISO 14660-2: 1999** [11], by default the circles obtained by the minimum square method are to be adopted, but they may be associated with other criterion that is advisable. The *"Collection"* of the points that are centres of the associated circles, joined together, constitutes the representative element from the hole's actual axis.

(10) *"Construction"* of the axis of the tolerance zone (cylinder with diameter 0,050 mm) by means of the intersection from two planes that are parallel to the associated reference planes obtained in (3), placed respectively at the theoretically-exact dimensions of 30 mm and 20 mm from references A and B.

The representative element from the actual axis of the cylindrical hole obtained in (9) must have all its points inside the ideal cylinder with diameter 0,050 mm, a cylinder of which its axis is the obtained in construction (10).

The elemental specification operations carried out on the functional elements of the parts, which are similar to the operations realized in the verification processes using the data obtained by means of coordinated measuring machines, allow to define a functional element by means of an integrative model that is valid for specification both in design and inspection stages. This model, that has been already studied by the authors [12], makes use of the same elementary operations in different stages of product development, thus contributing to reduce both the specification uncertainty and the correlation uncertainty, when those criteria for the association of ideal elements to the actual ones that better represent the function are chosen. This turns the GPS specifications into a tool of great utility for the treatment of tolerances along the concurrent design process that is dealt with in the next section.

4 Concurrent engineering and product development

Both the pure sequential and the product-oriented sequential models show quite a lot of limitations when incorporating new requirements, as for instance in the development of more complex and innovative products, in the incorporation to the product of new technologies that provide added value, in the necessary reduction of product design and development cycle times due to a progressive shortening of its life cycle, or in favouring the integration of CAD/CAM/CIM/CAE technologies and a better use of information and communication technologies (ICT) during the product design and development processes.

The concurrent model makes possible to manage better the company's resources, by integrating in a common project all of the functional areas involved in the product life cycle, aiming to reach an interdisciplinary collaboration in decision making, and supported by the use of shared data and information systems that allow to carry out in parallel the works of all the areas involved in product design and development. Also, with the permanent communication possibilities that the implementation of ICT in organizations provides, it is possible to create virtual concurrent engineering teams in which members have a part-time dedication to the project, and even they can be delocalized. The decisions adopted in concurrent mode allow achieving a higher product homogeneity and quality in products, which result in a greater reliability and interchangeability, and also a lower cost of them.

As is conceived by Yazdani [1], in the concurrent model, in each of the product design and development sub-stages it is necessary to have at one's disposal a number of entries in which the whole team will participate, where by means of several iterations successive design reviews are made to happen, in each one of which a new model is generated for the team to work on until the next revision, thus a more immediate and informal information exchange happening that favours concurrency. Other feature of the concurrent model is that changes are less definitive, due to the great dynamism that the various controls performed by the multidisciplinary team provide, because of what the design and manufacturing/verification reviews are happening simultaneously, after each of the iterations, thus shortening the product development time.

Relying on the mentioned principles of the concurrent model, in this paper tolerance design is conceived as a subset of the "product design set", in which specific resources and tools for tolerance analysis and synthesis are used with the aim of achieving a tolerancing optimization in a concurrent way, interacting with the product design model itself.

4.1 Integration of tolerancing into the concurrent engineering framework

When an enterprise organization makes the decision to implement the concurrent model for product design and development, just a few times sees tolerance specification as an extension of the interdisciplinarity among the engineering functions that are linked to the functional model design, the manufacturing processes, the verification, and the quality control of the manufactured parts, predominating the usual practices in which the tolerance allocation is made in the design process and from a basically functional perspective.

On the other hand, after the analysis performed in sections 3 and 4, contributions that are common to GPS geometrical specification and to concurrent design are shown to exist, as both of them have an influence on the product manufacturing costs (a better product specification entails a better process definition), an improvement in quality (more homogeneous products are attained and there are less rejections), and in both cases the cycle time for product design and development is reduced.

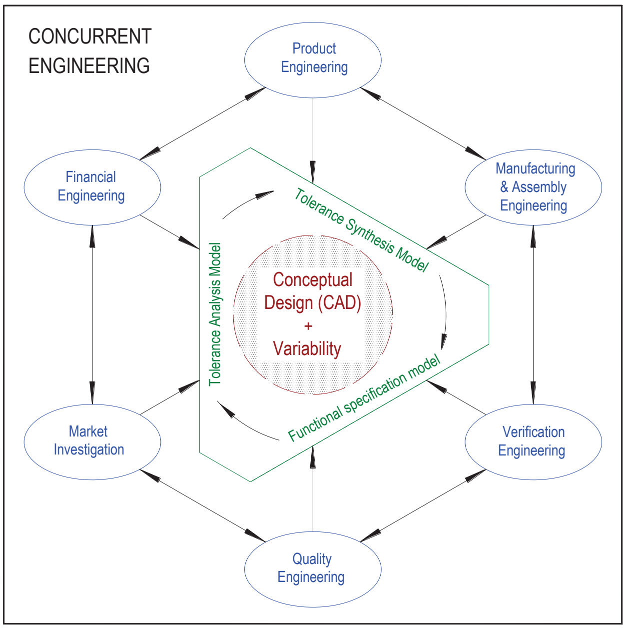

Fig. 6 Interactions in the product concurrent geometric specification process.

However, besides avoiding ambiguous specifications that do not integrate the functionality requirements by using GPS standards, it must be achieved that the distribution of tolerances corresponding to a functional condition among the dimensional chains' components provides also an answer to the problems associated to the remaining functions that interact in the product development process, shown in fig. 6, as the same functional requirement may be solved with different design solutions and with different distributions of the total tolerance. Because of that, the ISO-GPS standards' syntaxes and semantics turn out to be appropriate for establishing the necessary intercommunication among the engineering functions linked to the treatment of geometrical variability.

Lopez [13, section 4.3.2] argues that, generally speaking, as organizations in the past did not perceive the possibilities that tolerancing has to influence on products in reducing its costs, in shortening its design and development cycle times, and in improving its quality, the firms did not give to tolerances the importance that they have, and because of that the companies did not assign enough resources in order to provide the experts from the concurrent work group with a solid training on the subject. Usually, tolerances were only approached as a requirement to reach product conformity. However, when tolerances are a part of the concurrent model its allocation incorporates better the problems downstream, with less readjustments happening, and allowing to move forward quickly in defining the manufacturing processes and the resources for verification and control.

4.2 Proposing a methodology for concurrent tolerances design

The problems related to tolerance allocation have been dealt with by various authors, although always without reaching a concurrency approach as the proposed in this paper. Thus, Romero and Serrano [14] analysed different methods for tolerance allocation, focusing on functionality, although they already made reference to an evident relationship between cost/quality and geometric variability, which should lead to an implementation of methods for the integral management of quality out from the line. By their side, Aguayo and Soltero [15] propose tolerance allocation as a mathematical optimization problem among the design vectors, the tolerance vectors and other component variables, but referred it to general designs that did not focus on the specific problems of mechanical systems. Other authors such as Luna and Mendoza [16] proposed a methodology based on concurrent engineering to improve product and process engineering, in which tolerance allocation is considered as belonging to detailed design, where decisions on admissible geometrical variability are made based on a traditional approach to tolerances. Also, Chase [17] has developed functions for tolerance allocation for optimizing the manufacturing costs, and by their side Chen and Maghsoodloo [18] developed functions that combined manufacturing costs with the costs of poor quality, these two approaches being of great usefulness for optimizing tolerance allocation, but that can be further enriched by incorporating other influencing factors in the tolerance allocation process.

The central idea of this proposal holds the principle that the conceptual design of a product and its geometrical variability must be conceived in an integrated way and, as an extension of this principle, tolerancing must be considered as a concept in which three modules are interacting: the functional geometrical specification by means of the GPS language, the tolerance analysis and the tolerance synthesis, a concept that requires simultaneity of activities, retro-alimentation among the product development functions, and availability of shared, reliable and unequivocal information systems. Because of that, tolerance management cannot be conceived separately from the concurrent model that has been adopted, as the composition law applied for tolerance analysis has an influence on the verification procedures and the methods for product conformity, while the tolerance synthesis gives as a result a tolerance allocation corresponding to the condition that affects the manufacturing process planning.

As argued by López [13, section 4.3.4], once the central idea and the three modules interacting for tolerance design have been exposed, it's necessary to identify the links and tools for interaction, from design engineering, among the modules for functional geometric specification, tolerance analysis and synthesis, and the remaining agents of the product development process: Product Engineering (functional requirements), Manufacturing Engineering (manufacturing planning and process capability), Verification (resources and equipment for inspection, uncertainty management), and Quality Engineering (process control and variability statistic treatment), as shown in fig. 6. The methodology conceived in this paper can be named as "product concurrent geometric specification", consisting of a concurrent treatment of tolerances process in which the following inputs are considered in order to re-define the allocation model:

- Functional Design: To carry out a pre-allocation of tolerances.
- Detailed Design: To perform a concurrent tolerance design, oriented to the capability of the available processes and the costs incurred to obtain those tolerances by means of a specific manufacturing process.
- Estimation of costs caused by a poor product quality.
- Estimation of costs caused by reprocessing, rejections and warranties.
- Obtaining the combined cost-quality optimization function for each particular situation.
- Tolerance allocation for the functional condition using the former function.
- Place in common of the GPS specification that better expresses the target functional requirements and that is in agreement with the tolerance allocation obtained.

4.3 Activities to be performed in the proposed methodology

Taking into account the different factors intervening in the so-called "product concurrent geometric specification" and the variability transferred by them, depending also on what are the resources and the environment in each particular case, it is not possible to make a methodological proposal that is directly applicable to any company.

Taking as a reference the outline of activities or entries to the concurrent process that are considered in the final part of section 4.2, following are suggested the alternatives and the approaches that are considered appropriate to implement any of the activities from the methodological proposal.

4.3.1 Pre-allocation of tolerances in the design process

Generally speaking, by using the Quality Function Deployment (QFD) technique, in the product engineering stage the functional requirements –the product specifications– are found that best represent the product attributes conceived to satisfy both the explicit customer demands and his implicit expectations. The set of functional requirements is what Suh [19] calls the "functional domain of the product".

Taking the functional domain as a reference, the product concept pre-design is carried out where, according to fig. 1, the mechanical solutions and the geometric forms are obtained. Next, in the functional design stage an alternative is conceived to solve the predicted use and maintenance problems, and the dimensions of the geometric elements are fixed. Finally, in the detailed design stage the complementary geometries are defined, the dimensions of the design parameters to be considered in the manufacturing and inspection processes are established, and the geometric variability which is acceptable in each case –which is in reality another design parameter– is laid down.

The transformation of functional requirements into design parameters is usually done in an empirical way, based on the designer's experience and intuition, and its necessary later for the design to undergo successive improvement processes using trial-and-error methods.

In the methodology introduced in this paper a proposal is made to develop the transformation of the functional requirements into design parameters based on Suh's Axiomatic Design Theory [19] by means of a series of systematized stages, in which each of the initial functional requirements for a certain mechanical system is transformed into a design parameter that must be at the same level. It's somehow similar to a successive decomposition of a system into subsystems, and subsequently of these into assemblies, parts, geometric elements and admissible variabilities.

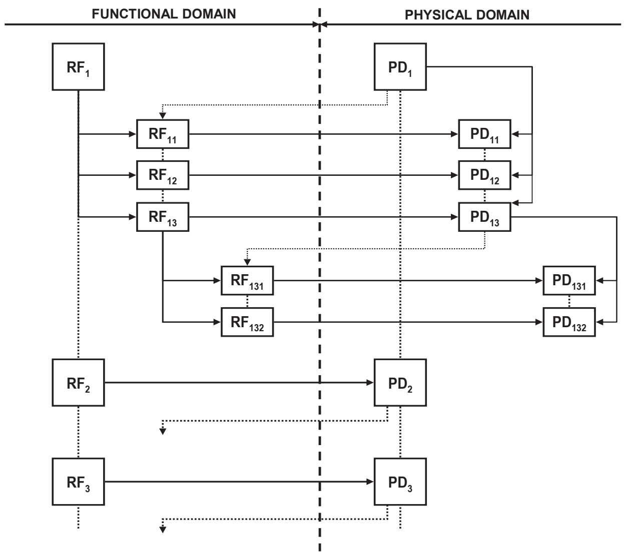

Fig. 7 Hierarchical levels in decomposition of product functional requirement and design parameters in each level.

A model for the decomposition of functional requirements into design parameters was developed by López [13, section 4.4.2], where a process such as the one shown in fig. 7 was proposed, where it's illustrated how each functional requirement (RF_i) must be transformed into an only design parameter, with the same concretion level and independent from others –exclusive to satisfy this requirement–, in such a way that when a parameter doesn't have yet the same level as a functional condition that could be expressed by means of a geometrical condition from the functional requirement it belongs to, the parameter must be decomposed into other functional requirements with a higher concretion level, each of them having a new design parameter which is independent and it is defined at the same level as that RF_i.

When a systematic approach as described above is adopted into the design decision making process, independence among the design parameters from each functional requirement is reached, so allowing to obtain an uncoupled design, i.e. a design in which the variation of a parameter affects only to a functional requirement, what becomes very important when this parameter is the admissible geometric variability. Also, the design so developed achieves traceability properties that facilitate possible further re-design processes.

The first stage of this methodological proposal consists in performing an initial allocation of tolerances, by means of the traditional method, once the former model is applied, aiming to the functional requirements decomposition providing a better identification of those design parameters that should be subject to tolerance exigencies.

4.3.2 Concurrent design for optimization of tolerance costs

Specified tolerances have a notable influence on the manufacturing cost and on functionality –i.e. on product quality–. Once a tolerance pre-allocation is made according to the indications of the previous section, this second activity aims to establish another tolerance allocation such that its values minimize the total cost of obtaining the whole of the product tolerances, while keeping at the same time its functionality level, which can entail for its part changes in other design parameters that are not tolerances.

Different methodologies can be applied for concurrent design of functionality and manufacturing costs of tolerances, one of them being proposed below.

A tolerance analysis is carried out, based on the first order of Taylor series expansion, as proposed by Chase et al [20], thus obtaining the implicit equations for the assembly functional restrictions with respect to independent variables –manufacturing dimensions–, geometric variables –specified geometric variables– and assembly variables. The coefficients in such equations are ordered into an matrix –tolerance sensitivity matrix–, and the tolerances of the chain functional elements in a second matrix.

The tolerance sensitivity matrix makes it possible to identify what are the tolerances with a bigger influence on the accumulated tolerance in the assembly process. If $[S_{ij}]$ and $[S_\alpha]$ are respectively the sensitivity matrices for the manufacturing and geometric variables, $[\Delta X]$ and $[\Delta\alpha]$ are the tolerance matrices for the dimensions and geometric variations, and $[\Delta U]$ is the matrix of variations produced in the assembly process as a consequence of the former, then:

$$[S_{ij}] \times [\Delta X] + [S_\alpha] \times [\Delta\alpha] = [\Delta U]$$

Once all the elements from the matrices above are known, it is possible to identify in the sensitivities matrix the tolerances that is advisable to modify in each case, which are the most influencing on the increase of ΔU_i.

By their side, the tolerance cost functions provide the cost (C) of obtaining a certain tolerance, using a general expression such as:

$$C = A + (B/T^n)$$

where A are the fixed costs, B is the cost of obtaining a certain tolerance value with a particular machine, T is the target tolerance, and n is a value that depends on the mathematical model being applied to calculate the tolerance cost –simple, squared, powered, exponential, etc.–. Thus, the problem can be defined as to optimize the total minimum cost by reducing those tolerances that are more sensitive to the variation transferred to the assembly, applying then the costs for obtaining such tolerances.

In this way, the initial model where tolerances are pre-assignated with the only aim of satisfying functional exigences, is changed here into a concurrent process that incorporates functionality, the costs of tolerance manufacturing with certain processes, and the capability of such processes to obtain the tolerance, giving way to a new model with which to work until the next review.

Other models can be applied that are more complex, and consequently also more precise. Thus, Zhang et al [21] developed a model for tolerance robust design that links together: functional requirements, costs, parameter –geometric and non-geometric– design, and tolerances. This model can be used to determine simultaneously those tolerances and the associated design parameters that minimize functional variations and satisfy the established limits for the manufacturing costs. These authors developed algorithms to evaluate system robustness taking as a reference the global variance obtained from each parameter's individual variance and weight factor, while the sensitivity factors are expressed as the ratio between the global variance, modeled with weighting factors of the influence of each parameter's variation on the functionality measure, and each parameter's individual tolerance.

4.3.3 Incorporation of the costs transferred to the user due to poor product quality to the tolerance concurrent allocation process

As the distribution of the functional condition tolerances among the different components of the dimension chain was conceived in section 4.3.2, it wasn't taken into account that as the product features move away from perfect quality or target value, so it increases the cost transferred to Society along its lifespan because of poor product quality. As a consequence, an increase in tolerance value reduces the manufacturing cost but at the same time it can result in an inadmissible quality loss.

It is necessary in many applications to take into account simultaneously the cost of achieving each tolerance using a particular process, and the cost transferred to the customer due to quality loss entailed by that tolerance value. Some proposals have been developed to minimize the combined total cost of tolerance manufacturing and the losses transferred to Society by the actual deviations from the target value. In this paper, the function developed by Cheng and Maghsoodloo [18] to optimize the combined total cost for the components of a dimension chain is proposed, because of its easiness of use.

In practice, often several critical dimensions coexist for the assembly that must be evaluated. In this conditions, frequently the same dimension (D_i) is involved in more than one dimension chain, and as a consequence, besides the variance of D_i –it is assumed that the variation of dimensions is statistically normally distributed, and that an amplitude of the tolerance zone of $T_i = 6 \cdot \sigma_i$ is adopted– $Var(D_i) = (T_i/3)^{1/2}$, a co-variance exists among the critical dimensions for assembly that share one same dimension among their dimension chains. The model developed by Peng et al [22] allows to optimize tolerance allocation, thus minimizing the combined effect of the manufacturing costs and the quality loss costs tranferred to the user, in those cases in which interrelationed dimensions with more than one critical dimension for assembly exists.

Regarding the cost of obtaining a tolerance using a particular process, some manuals exist, such as Todd et al [23], that provide orientating data based on which the costs for similar processes can be estimated. Little data is available about the costs transferred to the user because of poor product quality, as very wide studies are required for each of the possible mechanical functions, product types, conditions of use, etc.

When product competitiveness requires it, a tolerance concurrent allocation must be performed where, besides Design, Manufacturing and Inspection Engineering departments, also Product, Quality and Market Engineering departments must participate, with the aim of finding an optimized solution that achieves a balance among functionality, costs incurred to obtain tolerances, and losses caused to the product users because of poor quality.

4.3.4 Influence of product re-processing, rejections and guarantees on tolerance optimized allocation

There is always a difference between the number of units for which the raw material is supplied in the first operation of the manufacturing process for a part or component and the number of units being accepted –units conform to drawing specifications– at the end of the process. In each of the stages of any process a number –higher or lower– of parts are rejected, in some cases due to non-conformance to tolerances specified in drawings, having an impact on the costs that must be considered when optimizing tolerance allocation.

In some cases the parts out from tolerance can be recovered through re-processing operations, thus causing an over cost for the parts that must be considered when optimizing tolerance allocation, as a cost to reach that tolerance by means of the process being used. The cost of part rejections and re-processing are specific to each company, and therefore cannot be incorporated to cost-tolerance functions. Each company will obtain specific values to be incorporated to the optimization algorithm, according to the manufacturing process and the product to be manufactured, even if some initial estimation can be made based on values obtained from similar processes.

Furthermore, product issues and malfunctions along its guarantee period can be caused by unsuitable tolerance allocation, and in these cases it must be studied whether these costs are considered as manufacturing costs or as poor quality costs.

4.3.5 A function for optimization of tolerance allocation for a product

The considerations from sections 4.3.1 to 4.3.3 lead to the fact that, taking the mentioned general application methodologies for tolerance allocation as a starting point, for each product, process and company, a function exists that best optimize tolerance allocation, allowing to achieve the desired balance among functionality, tolerance manufacturing costs and poor quality costs.

As a consequence, the Product Engineering, Design, Manufacturing, Inspection, Quality, Maintenance, Marketing and Cost Management departments must participate in the process of concurrent allocation of tolerances, from the initial tolerance allocation each of them being progressively incorporated to the process, in order to perfection the successive tolerance splitting models that are generated at each planned entry for the tolerance concurrent design process.

The methodology for tolerance allocation proposed in this paper allows the planning of different concurrent levels, according to the demands, the manufacturing volume, the available processes … as in any case the cost and cost-effectiveness of the concurrent optimization study must be considered. It will be convenient in some cases to perform the optimization considering only the tolerance functionality and cost, while in other cases the cost of poor product quality for the user, rejections and/or guarantees … must be taken into account.

4.3.6 GPS specification of the obtained tolerances

The specification on drawing of the tolerances obtained in the optimization process can sometimes be performed by combining different specification elements, what could result in different meanings and interpretations of the same tolerance. This circumstance is seldom taken into consideration in the majority of research studies on tolerance optimization, which often disregard the fact that "a good optimization process for tolerance allocation, when it is not properly managed, results in a poorly efficient work".

The concurrent design team must define which GPS specifications get to express, univocally and without ambiguity, how each of the tolerances must be interpreted, as often different interpretations of the same specification are reached in the traditional treatment of tolerances when independent interpretations are performed in each stage of the product design and development process.

5 Conclusion

- When tolerance management is performed according to traditional practices, for any functional condition, the decisions on the tolerance splitting among the functional elements that are involved in such condition are mainly focused towards guaranteeing an optimal product performance, and seem to help poorly to face the current product competitiveness challenges.
- Geometric specification according to the current ISO-GPS standards is an essential tool for obtaining products with lower costs and improved quality.
- Implementation of the ISO-GPS standards is a fundamental requirement for an organization to be able to develop a concurrent tolerance design, but it must go together with a previous training about its knowledge and an efficient application, and also with an awareness of the firm management about its advantages and competitive contributions.
- When concurrent engineering incorporates concurrent tolerance design, it chooses the right path to achieve better costs and quality optimizations on the company's products, to reduce its development

cycle time, to increase its reliability and to raise the user's trust. All of the mentioned together are fundamental elements to improve the product's competitive level.

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