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ANALYSIS OF STACK-UP TOLERANCE USING ADJUST SYSTEM AND TOLERANCING

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Abstract. *The competitiveness between industries is increasing drastically, so they seek higher quality and productivity. In this context, lower manufacturing cost become core function to achieve these goals. This competition in the field of mechanical manufacturing plays a profound impact on the sizing of the final costs of manufactured components, in particular the definition of mechanical manufacturing tolerances. The importance of a well-defined tolerance is associated to the fact that, the result of these stack-up tolerance sums in mechanical assemblies will be the main goal, which will influence the perfect functioning of the product. For this purpose, studies assessing the behavior of the tolerances distribution of the parts need to be done and there are effective tools to manage these dispersions. These tools focus on different fields of the project's phases and evaluate the distribution of tolerances for individual component, and a stack-up of dimensions. This analysis and the management of the tolerances accumulation between iterations is the central challenge of the mechanical design and manufacturing. The choice of a particular technique depends on the association of economic risks (scrap, productivity, quality) which the process is willing to assume. This work aims to present the associated results of the tolerance unity (IT) to probabilistic methods involved in the analysis of stack-up tolerance. The experimental analysis justifies the combination of IT and a statistical method as an appropriate choice of setting tolerances.*

Keywords: *mechanical design, stack-up tolerance, unity tolerance, tolerance synthesis.*

1. INTRODUCTION

The industries are drastically increasing the search for higher quality at lower manufacturing cost and higher productivity. For mechanical engineering, these objectives are considered in the stages of design and mechanical manufacturing. In this context, the designer starts the breakdown of design using as reference instructional tables available in handbooks or national and international standard instructions about fits and tolerances. In the manufacturing, the process analysts have access to the capability of their machines and they will decide the best factory condition associated with the components assembly. So, setting the appropriate tolerances in the stages of project involves determining the design tolerances and realization of manufacturing processes.

Generally, the parts are designed with open tolerances, which lead to the risk of loss in the process and therefore increase cost. In contrast, designing parts with tight tolerances require processes with high capabilities, which will also raise the cost due to the need for precise machines. Thus, it is evident that there must be a balance between design and manufacturing process, where costs are acceptable.

Analysis and synthesis of tolerance studies are in the design and process phases respectively, seeking to maintain the tolerated dimensions in synergy with the cycle of design, manufacture and assembly of products. Among these steps, there are two techniques that depend on the association of the economics risks admissible: Worst Case and Statistical Methods. These are mathematical models that perform the study of the tolerances interaction when the dimensions of the parts are grouped in sequence or when they form a closed loop of dimensions.

More conservative and expensive, the worst case considers the absolute limits of the process in its model and it is represented by the sum of the parts tolerances that form the evaluated set. It is evident that the project's dimension should be fully reproduced in the manufacturing process without rejection, as a case of total interchangeability. The statistical method assumes that processes are inherently probabilistic and it uses the central limit theorem to formulate its mathematical model. It relates the properties of the Gaussian distribution and establishes the relationship between the variance of the assembled groups as values of the components' variances that is part of that group.

The estimated tolerances in project persist in the worst case analysis, which leads to the determination of the stack-up dimensional functional condition that do not match the reality of the processes. Since the production processes are events subject to uncontrolled or poorly controlled influences and with high adherence to manual processes, any deterministic analysis rather than probabilistic is incoherent, except if it is related to parameterization. Thus, considering the context, this work aims to study a method of analysis of the stack-up dimensional variations that occurs in mechanical assemblies as well as presents their reflections on the functional requirements. In addition, an experimental study was conducted with data from manufacturing of a set of mechanical part of a dedicated hermetic refrigeration compressor to mark the conclusions.

It is evident the importance of well defined tolerance, and this fact implies that in mechanical assemblies, some dimensions are more important than others and some dimensions must be less tight, since final or functional tolerance of mechanical assembly is affected by the sum of the individual tolerances of the set (Bjork, 1978). Furthermore, the appropriate selection of these limits is a key element to increase productivity, develop a quality control of the product, increase profits and significant savings (Teeravaraprug, 2007).

2. TOLERANCE

Throughout the mechanical design, criteria of materials resistance are associated to the dimensions assigned to the proper functioning of the product and manufacturing processes so this operation becomes real. This combination allows companies to be competitive, since they lead to higher quality with lower manufacturing cost and high productivity of parts (Zou et al., 2001; Swami et al., 1995).This competitive environment plays in the fields of manufacturing and mechanical design, a profound impact on the sizing of the final costs of manufactured components. Despite the many existing manufacturing processes, a cornerstone needs to be evaluated and questioned many times during the development of a project: mechanical manufacturing tolerances (Teeravaraprug, 2007).

Manufacturing processes are inherently inaccurate due to various characteristics that affect system, such as: type of manufacturing process, temperature, properties of the machined material, tools, lubricants, clearances between machine elements, measuring methods (Voelcker, 1998). Such influences are combined causing a dimensional variation of the manufactured part. Consequently, the mechanical designs consider a permissible variation on dimensions, called dimensional tolerance.

Setting a proper final tolerance of a mechanical assembly is a difficult task. One reason is that tolerance is highly distributive since it is difficult for a designer to take into account the cumulative effects of all possible combinations of the variation of the project's characteristics. Sometimes, the tolerances are determined with strict values which increase the manufacturing cost (Laperriere et al. 1999). In contrast, the dimensional variations or tolerances that are designed and controlled without liability can cause problems during assembly of the sets, requiring extensive rework, large wasted lots, shutdowns in assembly lines, and causing damages in product performance and customer dissatisfaction (Drake, 1999).

The reported facts reflect the necessity of a definition and inherent study of the relationships in which dimensional tolerances are characterized during manufacturing, design and assembly of mechanical devices. It can be argued that the tolerances are the first tool to control a project, exercised through the selection and process control and inspection procedures. The set described in section 3.1 is used to find a good design tolerance, which can be represented by numerical or absolute limits and statistical inferences for its definition.

Then, the possibilities of defining dimensional tolerance for use in the design, manufacture and assembly of mechanical devices:

a) a specified precision in a continuous region in which their extremes are referred as limit regions which are defined as the maximum limit and minimum limit (Bjorke, 1978). The same author also defines tolerance as the absolute value of the difference between the maximum and minimum dimension;

b) it is essentially smaller angular and linear displacements of a functional element regarding a nominal position (Laperriere et al. 1999);

c) ABNT (NBR6158/1995, p. 4) defines as "the difference between the maximum dimension and the minimum dimension, i.e. the difference between upper and lower clearances" referred to a number of principles, rules and tables that are applied to mechanical technology, more precisely to the system of tolerances and fits; and,

d) ASME (Y14.5M 1994) defines it as a specification of the total dimensional variation allowed. The tolerance is the difference between the maximum and minimum dimension.

It is important to note that specifying, defining types and report values of tolerances are already explicit in normative instructions already mentioned. However, the standards do not dictate a method of the tolerances should be specified (ASME, 1994). Until 1990, elements were tolerated based on information from manuals of machines elements, knowledge-base developed along the designer's experience or automatic systems that designate tolerances based on the function of the device (Salomons et al., 1996).

Until these days there is no clear discussion of this issue, the ASME Y14.5 and ISO 1101 have been set up to ensure proper communication of dimensional and geometric tolerances (GD&T) however, it can be noted that these standards were developed with information gathered over years of engineering practice rather than mathematical principles. This tends to two problems (Voelcker, 1998):
i) the lack of communication and misinterpretation of design specifications by designers, quality departments, customers and even the unavailability of complete three-dimensional analysis of stack-ups tolerances involving all types of dimensional and geometric variations; and,
ii) it tries to replace the rules completely are an unacceptable proposal to the industry that believes that it will represent the loss of empirical knowledge.

2.1 ANALYSIS AND SYNTHESIS OF TOLERANCE

Assigning tolerances to mechanical components is not an easy task as starting during the project and it extends to the setting of tolerances that compose the final functional dimension of the set. The literature assigns two distinct fields for this analysis. The first is the tolerance analysis, in which the designer distributes some of the components' tolerances and observes the functional condition of the mechanism while the synthesis of tolerance aims to determine the critical tolerances of the components that contribute to the functional condition of the engine. Laperieri et al. (1999) used chains of coordinate points in relation to the functional dimension and applied the concept of homogeneous transformations and Jacobean transformations for linking the two phases of size tolerances.

In traditional design and manufacturing practices, the tolerance analysis of the design and manufacturing dimensions are sequentially developed based on the designers experience and non-optimal methods. Usually for the first stage of the project, specified tolerances are based on the product function and some normative instructions (Zhang et al. 1992). However, a set of mechanical parts contains many features that involve tolerances and these features interact with each other and pile up (Voelcker, 1998). This means that assembled parts results in the sum of the final dimensional tolerances of those components. And to achieve high precision of the final assembly the parts need to be produced with tight tolerances which increase costs of the product (Kannan et al. 2003).

Engineering offers effective tools that work to manage and minimize the impact on the cost of the product when the project phases interact with the process, studying the evaluation and distribution of tolerances for individual components as well as a stack-up of dimensions. This analysis and the management of the accumulation of interactions between tolerances is the central projects challenge in manufacturing (Voelcker, 1998).

Tolerance analysis and synthesis of tolerance are in general studies assessing the behavior of the tolerances distribution during the execution of the project, at the designers table and during the manufacturing processes. Tolerance analysis is a function of Design while the synthesis of tolerance is related to the production. However, for efficiency and economy in manufacturing, both studies must be carried out (Zhang et al. 1992; Voelcker, 1998).

In some papers tolerance analysis is a global term that includes two subcategories: the first describes the method used to determine the specifications of the individual tolerances of the parts corresponding to the project, and the second is a process of determining the cumulative variation possible between two or more parts or geometries that come together in a loop. This second part of the definition is a technique commonly called Stack-up Tolerance (Fisher, 1994). The term refers to a technique used for calculating a variation of a single non-tolerated distance in the design.

Ciurana et al. (2004) described the goals of running a project using terms created for such development. They started studies defining dimensions used in projects which have different meanings in design and manufacturing. A set of dimensions is that the Functional Dimension is a dimension identified in the project that ensures the correct operation of the mechanical assembly. It is also used to define a reference to a dimension stack-up related to the project, establishing dimensional and geometric tolerances of its components. Thus, the functional dimension of mechanical assemblies is evaluated for the synthesis of tolerance within the context of stack-up tolerance and introduces the nomenclature functional condition rather than functional dimension. Zou et al. (2001) described the tolerance analysis as an assessment of appropriate allocation of tolerance which can lead to lower costs of assembly and setting a high probability of fitting and reducing the rejection or the amount of rework.

In the addition to the development of the Functional Condition, some adjustments must be defined and distributed along a dimensions stack-up or geometric elements, and also the specification of new tolerances. This process involves the use of tools such as CAD, to manage and calculate it, since this problem cannot be treated without considering all the parts or geometric features involved in the assembly of the set (Ciurana et al., 2004).

Synthesis of tolerance involves a process called tolerance allocation, which analyzes the tolerances between all the dimensional components of a stack-up that involve the assembly of a set, ensuring product specification and functionality. Tolerance Allocation can also be understood as the study of the process behavior used to determine tolerances for each component and its association stack-up. The synthesis of tolerance can be categorized into two types which are: i) worst case, and ii) statistical methods.

2.1.1 WORST CASE

The concept of worst case stack-up tolerances (TWC) is to sum the tolerances of individual components (T_i) of the elements composing a stack-up, ensuring through its mathematical model, as can be seen in Eq. (1), the maximum tolerance of components assembly and thus, ensuring full interchangeability between these components.

$$TWC = \sum T_i \tag{1}$$

It is noted that the method works with absolute numerical limits of tolerance. T_i is the tolerance of each part that composes an assembled set. If TWC is greater than the functional tolerance, it will be necessary to review and redistribute tolerances between the components, thus providing closer tolerances between them, or it will be necessary a inspection of the 100% of components to ensure the functional tolerance. This is only one of the possible ways to analyze the problem. It can be realized that it is an expensive method, since it works with tight tolerances, which usually can require processes with high levels of capability.

Hassani et al. (2008) proposed a new approach to tolerance analysis based on worst case applied to a linear tolerance stack-up and comparing results with a statistical method (Monte Carlo). Their results attribute a better approach in the selection of IT's with pieces of the stack-up by comparing the waste rate between the methods.

2.1.2 STATISTICAL METHODS

The low probability of the combination of worst case occurring is statistically taken into consideration. Basically the traditional statistical method, root sum of the square (*RSS*), considers the combination of the dimensions measured variances of each part involved in an assembly, and so estimating the number of defects that can occur. The *RSS* model assumes that the produced dimensions are in a normal distribution and then postulates that is easier to produce parts around the statistical mean. For this, it considers the limits of $\pm 3\sigma$ to probabilistic tolerance and analysis model as in Eq.(2).

$$T_{RSS} = \pm 3\sqrt{\sum \sigma_n^2} \tag{2}$$

where σ_n is the measure of the sample standard deviation of each part involved in an assembly and T_{RSS} is tolerance calculated by the method.

Teeravaraprug (2007) made a comparative study of the statistical methods and the worst case by comparing models that considered the cost of assembly as key factor. He concluded that the statistical method results in lower costs than other methods when it is considered only the manufacturing analysis. Another variation of the method is the so-called statistical estimated model of mean-shift (Drake, 1999).

In order to increase the quality levels required in the global electronics industry Six Sigma program uses this concept to manufacturing processes (0.002 defects per million). The model six sigma developed by Motorola to evaluate tolerances was formulated taking into account a factor K which quantifies the mean-shift suffered by each individual distribution of the components, as in Eq. (3).

$$\sigma_{mont} = \sqrt{\sum \left(\frac{Ti}{3Cpi(1-K)}\right)^2} \tag{3}$$

where C_p is the capability index of the measured dimension and k is the factor that must be observed during manufacturing and can be assigned between 0 and 1 (Chase, 1990).

There are also still advanced statistical methods which consider non-normal distributions in their models. These methods give much better estimates of the number of rejections than a simple statistical analysis method when the distribution of cases is well known and two aspects are taking into consideration: Monte Carlo Simulation and Moments Method (Trabelsi et al., 2000).

3. EXPERIMENTAL ANALYSIS

In a mechanic assembly the functional condition it was defined by the differences between dimensions. To study this concept, it can be used, at first, the expansion by Taylor series with $f(x)$ as $g(x)$, as in Eq. (4).

$$G(x) = G(a) + G'(a)(x-a) + \frac{G''(a)}{2!}(x-a) + \cdots + \frac{G^n(a)}{n!}(x-a)^n \tag{4}$$

If it is considered that functional condition is the difference between the nominal dimension of a hole (D_n) and the nominal dimension of the shift (d_n), the result is in Eq. (5).

$$G = D_n - d_n \tag{5}$$

Then, if it is considered several assembly sets, the Eq. (5) can be expanded as seen in Eq. (6).

$$G(x_1) = D_{x1} - d_{x1}\,, com\ x = 1 \ldots n \tag{6}$$

The function of an assembly can be clearance or interference. Considering a system with clearance, the maximum clearance can be defined as in Eq. (7).

$$\begin{cases} D_{x1} = D_{ni} + Ai_i + \Delta x_i \\ d_{y1} = d_{ni} + as_i - \Delta y_i \end{cases} \tag{7}$$

where Ai_i is the inferior distance of the hole, as_i is the superior distance of the shift and Δx_i and Δy_i are the positions of the tolerance in the tolerance zone. The terms of the Eq. (7) are represented in Fig. 1.

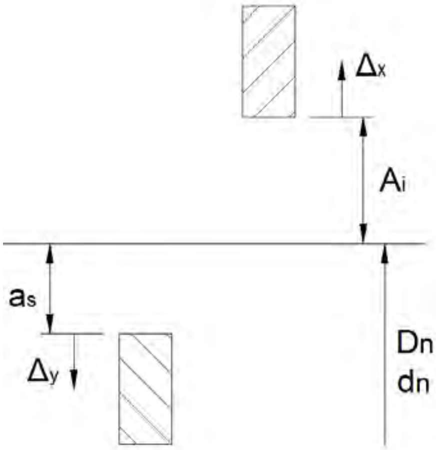


Figure 1.Tolerances zone.

The combination of the concepts in Eq. (6) and (7) is expressed in Eq. (8).

$$\begin{aligned} G(x,y) &= D_n + Ai_i + \Delta x_i - d_n + as_i + \Delta y_i \\ G(x,y) &= (Ai_i + as_i) + (\Delta x_i + \Delta y_i) \\ G(x,y) - (Ai_i + as_i) &= (\Delta x_i + \Delta y_i) \end{aligned} \tag{8}$$

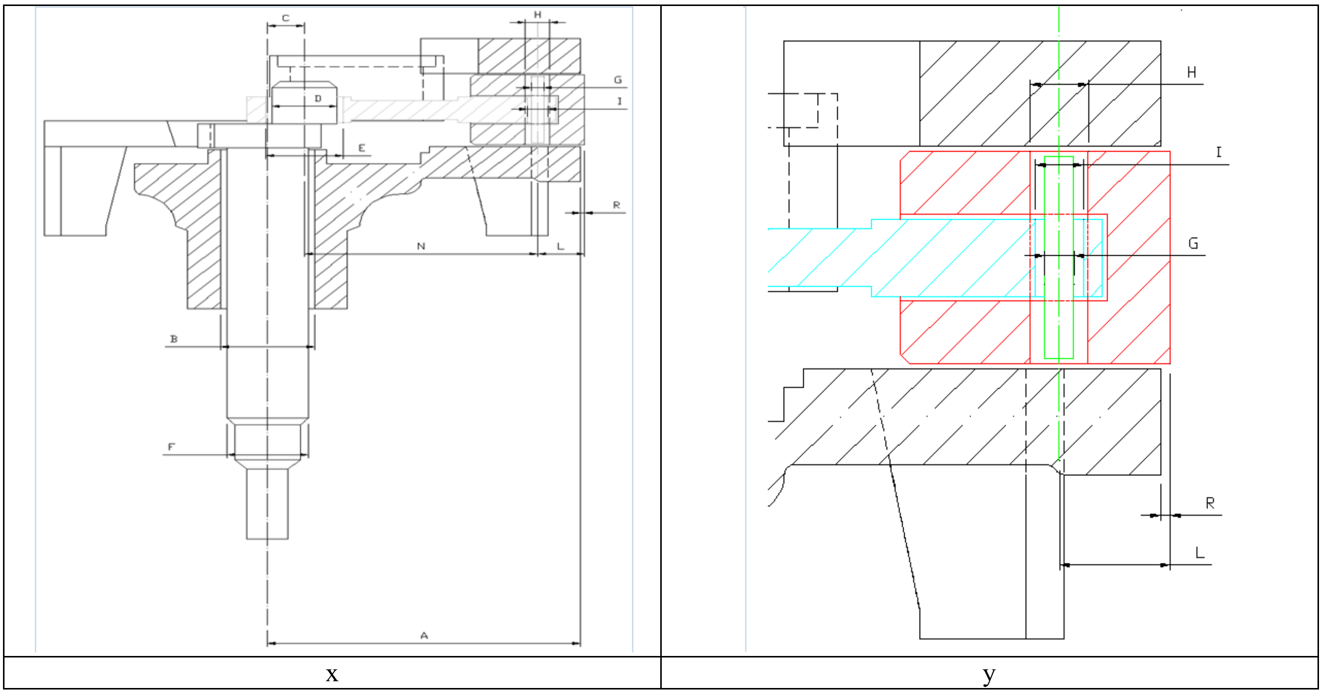
The same mathematical manipulation can be applied for the calculation of the minimum clearance as in Eq. (9).

$$G(x,y) = (Ai_i + as_i) - \left(\sum \Delta x - \sum \Delta y\right) \tag{9}$$

Equation (9) will be used during the application of the studied method to generate the experimental data which is the goal of this work. The functional condition can be defined as in Eq. (9) and it can be associated with the propagation of tolerance limits by maximum clearance.

3.1 STACK-UP TOLERANCES DEFINITION

The component used in this study is represented in Fig. 2, which corresponds to a set of mechanical part of dedicated hermetic refrigeration compressor. Letters identify the components that compose it and the function defined in Eq. (10) is represented by the letter 'R' in Fig. 2(y).



x

y

Figure 2. (x) Studied mechanism and (y) mean shift detail.

The basic operation is the rotation of the axis represented by "F" which enables the eccentricity "C" to transform this rotation into a translational movement of the piston "P," like a connecting rod mechanism. One of the critical features responsible for the quality of the efficiency of this engine is the distance "R" shown in Fig. 2 and identified by name in this study as Functional Condition. It is from the functional condition that it begins the defining schema of the assembly parts to represent a closed cycle of dimension. It is important to note that the choice of a stack-up is based on the lowest number of vectors involved in the loop.

Functional condition is a distance represented by a dimension and a tolerance. This dimension is defined as functional dimension and the tolerance as functional tolerance. Viewing Fig. 2(y) and identifying Functional Condition "R", the equation that represents the stack-up is defined by the representation of the dimensions regarding to the mechanism through dimension vectors: if it has direction to the left of "R", it will receive a negative sign and thus, dimension vectors with direction to the right have positive sign.

After analysis of the mechanism, the parts that compose the assembly to form the closed cycle regarding to the functional dimension are identified and the dimension of each part is individually considered in the design and the capabilities of the manufacturing processes are collected. Figure 2(x) identifies through the upper letters each dimension that composes the dimension vectors of the stack-up. They are: ‘R’, ‘L’, ‘A’, ‘F’, ‘B’, ‘C’, ‘D’, ‘E’, ‘N’, ‘H’, ‘S’, ‘I’. Adopting the direction to the left of ‘R’, it initiates the description of the stack-up. The first vector is represented by the letter ‘A’ and it is described in the mechanism as milled face to the center of the burnished cube as can be seen in Fig. 2(y). This routine will be applied until to complete the development of the tolerances stack-up.

The cycle of the stack-up can be visualized in Fig.3 and the equation relating the functional dimension R is represented in Eq. (10).

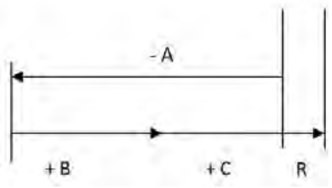


Figure 3.Cycle of the proposed chain.

$$R = -A - b + C - d + E - F - G + H \tag{10}$$

Table 1 contains important data on the effect of the propagation of tolerances for the definition of the functional condition. The dimensions were not evidenced with the purpose of protecting industrial design data.

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Table 1. Experimental results of production process of the studied mechanism and of the tolerance calculation.

Vector	**A**	**B**	**C**	**D**	**E**	**F**	**L**	**H**	**I**	**G**	**N**
Project	*	*	*	*	*	*	*	*	*	*	*
Tolerance[(1)]	**0,0760**	**0,0080**	**0,0300**	**0,0160**	**0,0160**	**0,0080**	**0,0500**	**0,0076**	**0,0050**	**0,0080**	**0,0500**
IT	9	5	9	7	7	5	9	5	4	6	9
Process	**Milling**	**Burnishing**	**Grinding**	**Grinding**	**Reamering**	**Grinding**	**Burnishing**	**Grinding**	**Burnishing**	**Reamering**	**Reamering**
Standard Deviation	*0,0121*	*0,0016*	*0,0018*	*0,0005*	*0,0003*	*0,0080*	*0,0040*	*0,0020*	*0,0050*	*0,0040*	*0,0050*
3σ	*0,0363*	*0,0048*	*0,0054*	*0,0015*	*0,0009*	*0,0240*	*0,0120*	*0,0060*	*0,0150*	*0,0120*	*0,0150*
Skewness	*-0,1709*	*-0,5400*	*0,6145*	*-0,4158*	*-0,3000*	*0,6200*	*0,1891*		*0,8425*	*0,1100*	*-0,2000*

(1) millimeters

Table 1 contains measured values of the manufacturing process of the components shown in the stack-up under consideration. In Tab. 1 are shown the values of tolerance of the components that will be determined in the design phase. It also determines the value of IT (line 4 of the table) of each process that will be used as reference. The IT's mentioned in Tab. 1 are pre-selected based on their functional condition. As can be seen, the standard deviation values show that the behavior of some processes have capability insides of the limits specified by IT while others are above the established tolerances.

The experimental data were collected by analyzing the capability of the machines that manufacture the part. Then it was analyzed in the stack-up tolerance. Figure 4 represents data from the reamering process of vector E.

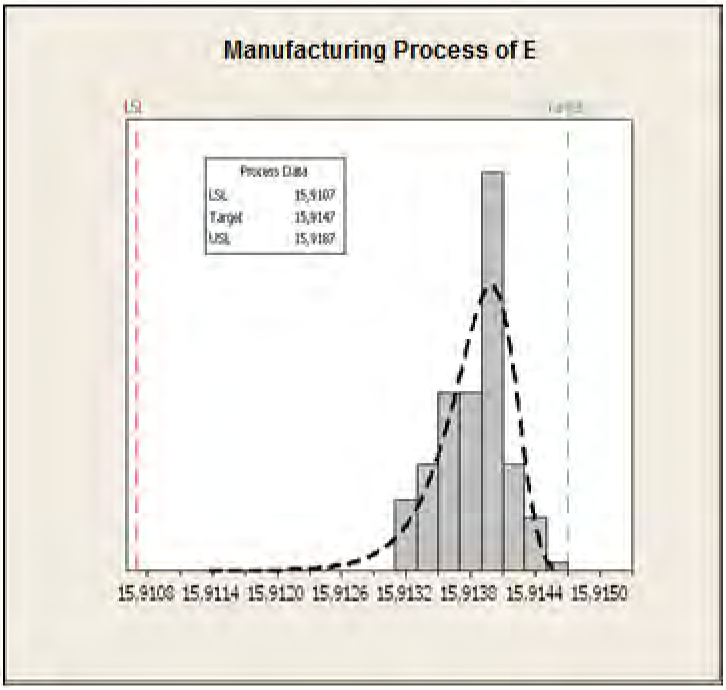

Figure 4.Cycle of the proposed stack-up.

As can be seen in Fig. 4, data show a mean shift behavior and skewness which represents the production close to the mean values but in the inferior limit region.

4. CONCLUSION

In order to study a method of analysis of the dimensional changes accumulation that occurs in mechanical assemblies, an experimental study was conducted with data from manufacturing of a set of mechanical part of dedicated hermetic compressor refrigeration. The first step was to define the components which compose the stack-up tolerance and so determining the functional condition. Using this concept, it was collected production data of the stack-up components. These data were used in tolerance analysis of the statistical method. As can be seen in the case studied, the generated data can be used to adjust a better IT to the process, thereby minimizing the project time.

The quota selection of the parts in the studied mechanism as the objective of defining the functional condition can be better assessed with the propagation of tolerances during assembly of this mechanism considering techniques of statistical models. The data collection process is relevant in this technique providing the best determination to evaluate the IT stack-up dimensions. The development of this technique becomes complete with the restriction of maximum clearance for the functional condition.

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