Tolerance Management for Assembly – Not a Matter of Product Size

Rainer Müller, Martin Esser, Christian Janssen, Matthias Vette, Stefan Quinders

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Prof. Rainer Müller, Dr. Martin Esser,
Christian Janßen, Matthias Vette, Stefan Quinders

Laboratory for Machine Tools and Production Engineering (WZL),
Chair of Assembly Systems, RWTH Aachen University
{R.Mueller, M.Esser, C.Janssen, M.Vette, S.Quinders}@wzl.rwth-aachen.de

Abstract. Today's industrial assembly systems have to enable individualized production as well as to feature a high degree of automation to cope with both quality requirements and increasing cost pressure. An overall tolerance concept is necessary to allow processes under the above referenced conditions. Reducing costs and the complexity of assembly processes can be achieved by an assembly product design based on the information provided by a tolerance analysis. This paper describes industrial standards and innovative concepts of a holistic tolerance management that are independent of product size.

Key Words: tolerance, key characteristics, tolerance chain, assembly

1 Introduction

Almost all of today's industries, independent of the product's size or costs, are affected by the progressive globalization, a fast technological development, changing resource conditions, growing product complexity, increasing product variants and a shorter product life cycle. Assembly systems and processes are particularly exposed to the pressure to reduce production costs because they play an important role regarding the value in the manufacturing process.

To meet the referenced requirements, strong tolerance management methods are necessary. Otherwise the adaption of an assembly system to continuously changing tasks in minimum machine downtime will not be possible.

To provide examples, tolerance management approaches for aviation and electronic industries are shown. Although there is a large difference in product size, both industries show numerous parallels regarding the requirements, like a quick integration of new products and a growing number of product-variants.

The lead approach is to cut down assembly costs by reducing the complexity of the assembly processes and the equipment by using an intelligent tolerance management system which offers the possibility to select simple processes that can be performed with low cost assembly systems.

2 Basics of Tolerance Management for Assembly Processes

The development of an assembly system is based on a stringent planning logic as shown in figure 1. To satisfy the customer´s requirements high-quality products are needed. The customers' requirements and/or the globalized market exert the cost and quality pressure on the product. The assembly process is defined on the basis of the product analysis. A process analysis determines the specification of the assembly equipment.
For optimization of the product design, the assembly processes and the equipment a feedback loop is needed. In the following section, the four major steps, "Product Analysis", "Design for Assembly", "Process Analysis" and "System Optimization" will be explained while considering tolerance management concepts.

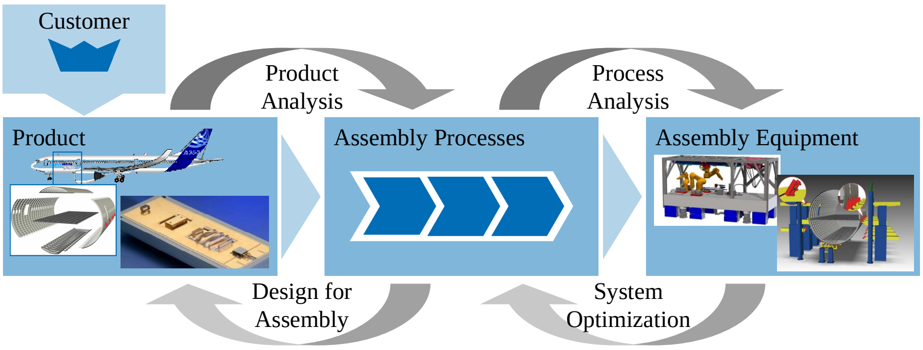

Fig. 1: Logic approach for the development of new assembly equipment

As already mentioned above, this paper demonstrates the topic with examples from aviation and electronic industries. There is an airplane which is assembled in large jigs and assembly stations versus a slab-lens marking laser (80mm x 200mm) which is assembled in a reconfigurable and fully automated assembly system. The challenge in laser assembly is to position all lenses on one level for optimal laser-beam characteristics. The relation between the product's size and the assembly accuracy is similar.

3 Product Analysis

At first the products precedence graph has to be set up. The precedence graph indicates the sequence requirements so that one possible order of the assembly processes is given.
Out of the product specifications a large amount of tolerances and product-characteristics are given for manufacturing and assembly processes. But not all tolerances are important for all steps in assembly. Therefore, identifying the most important tolerances for the assembly processes is one of the major challenges of a strong tolerance management. These important tolerances are the Key Characteristics

of the product and can be identified by the use of the Key Characteristic Flow-Down method which is described in the next chapter.

The term Key Characteristic (KC) describes a quantifiable characteristic of a product, part, or part of a process whose deviation from the specified set point results in unacceptable impacts on the product's costs, function or safety [1]. To avoid these effects, the deviations of the KCs are limited by tolerances, and the compliance of the tolerances can be implemented within the assembly process.

There are a lot of tolerances within the product specification for the final product and for all single components.

A consideration of all tolerances generates high costs for the assembly process. Therefore, the challenge for the product analysis is to decide which tolerances are essential for the assembly process and must be identified as KCs. Furthermore, the traceability of tolerances back to why they are needed is important for an understanding of the assembly process definition and optimization.

3.1 Approach to Identify Admissible Tolerances

An essential part of the method of KCs is the Key Characteristic Flow-Down, where the relation between the customer's requirements and the components or module KCs is shown [1]. Developing the KC Flow-Down follows the top-down approach from the customer's demands to the point where these demands are broken down into individual and measureable KCs [2]. From these components KCs relevant assembly processes are derived [1]. In case of the slab-lens marking laser, for example, the tolerance of the lens' position relative to the crystal is identified as a relevant KC for the assembly process, because of its direct influence on the quality of the laser beam. On the other hand, there are tolerances which are not taken into account because they are irrelevant for the execution of the function. By applying this method, the number of specified tolerances could be reduced from initially 36 to 12, so that the effort in planning the assembly system was significantly reduced. The described method for focusing on the relevant product functionality helps to achieve this result [3]. Focusing on the special KCs during the assembly processes helps to reduce the considered product characteristics and helps to simplify the assembly processes.

3.2 Evaluation and Classification of Key Characteristics

An example of the aircraft assembly (figure 2) helps to explain the context of the evaluation and classification of relevant KCs. There are KCs for all kind of product characteristics. For this example the geometric KCs are focused. These are classified in three different groups. Performance Key Characteristics (PKCs) are related to the fundamental and top-level KCs who determine the overall design and aircraft performance. Assembly Key Characteristics (AKCs) guarantee the assembly capacity in the following process. Manufacturing Key Characteristics (MKCs) are part of the physical feature of each elementary part or tool [4].

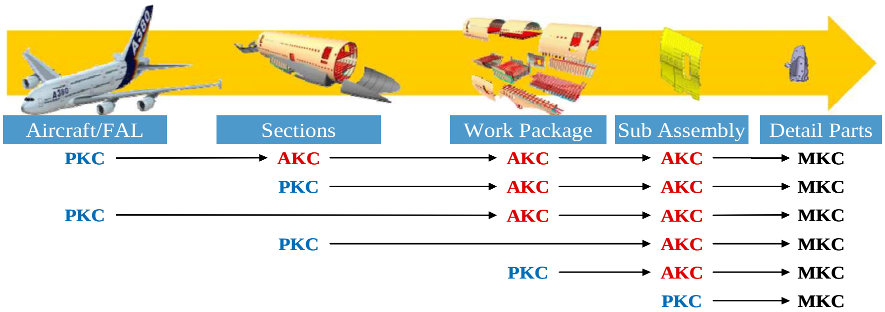

Fig. 2: Classification of the Key Characteristics in aircraft assembly [4]

Figure 2 shows the application of the referenced classification for an aircraft assembly beginning with a single part and ending in the final assembly line. At the lowest level there are only MKCs due to the manufacturing accuracy of single parts. The AKCs are quality gates which must be reached to enter the next stage within the assembly process. The PKCs directly influence the flight performance and the cockpit ergonomics. Using the method of classifying the KCs helps to figure out the reason why PKCs cannot be hold in a late stage of the assembly process. The diagram guides the user directly to all reasonable KCs in former assembly steps and helps to find the critical assembly process or a single part which is out of the tolerance. But this traceability of tolerances can only be done if there is an exact understanding for the assembly processes and the used technologies.
A feedback loop for product optimization may be titled “Design for Assembly”. It will not be in focus here but is based on the knowledge of the assembly processes and technology and the “Product Analysis”. Concepts and design guidelines can be found in literature [5, 6, 7].

4 Process Analysis

Deviations in assembly processes may result from manufacturing inaccuracies, the used technology and from assembly equipment. To recognize the deviations in an assembly process, a visualization of the processes is absolutely necessary. Tolerance chains offer a comprehensible tool for the visualization of tolerance problems in the process analysis and equipment planning. Figure 3 shows the tolerance chain for an aircraft section assembly. All section components (lower, upper, side shells and the floor grid) are positioned by the assembly equipment. The vertical section diameter is one of the main AKCs and will be decomposed as shown in the tolerance chain. Each knot of the tolerance chain symbolizes one datum of the product or the assembly equipment, thus the consideration includes both the component tolerances caused by the manufacturing process and the assembly tolerances by the equipment. The links describe the uncertainty or the deviation of specific values between two knots. This method splits the complete assembly process in single subsystems. Thus, the visualization of tolerance chains enables an easy overview in complex processes by breaking down the entire system into subsystems.

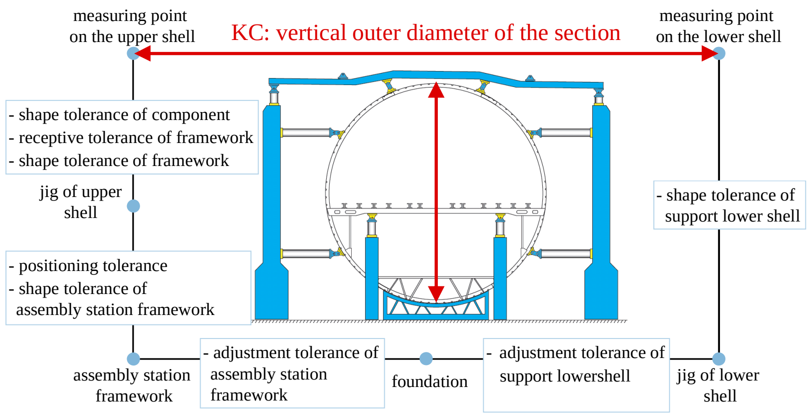

Fig. 3: Tolerance chain for an aircraft fuselage section assembly

The tolerance chain starts at the measuring point on the upper shell. Then it reaches the jig of the upper shell and the assembly station framework. The next steps are the foundation, the jig of the lower shell and the measuring point on the lower shell.
From the derived information, external measurements and expert knowledge it is possible to estimate the accuracy of each link.
Now, it is possible to assess the assembly-ability of the assembly process. Therefore a tolerance analysis for the entire tolerance chain is carried out. To determine the maximum/ minimum deviation of the tolerance chain, the chain's links with their maximum/ minimum tolerances are added. [8]

$$T_{MAX} = \sum_{i=1}^{n} t_{MAXi} \quad \text{bzw.}$$

$$T_{MIN} = \sum_{i=1}^{n} t_{MINi}$$

T_{MAX}	maximum of the tolarance chain
T_{MIN}	minimum of the tolarance chain
t_{MAXi}	maximum tolarance of the component i
t_{MINi}	minimum tolarance of the component i
n	number of components within the assembly

When a mounting capability is given by this maximum/minimum method, a complete replacement of the individual components is possible and the assembly will always be successful [7]. Assuming, however, that the existence of individual tolerances is random, and that they do not represent a specific trend or a systematic error within the assembly process, a worst-case scenario would lead to unnecessary costs and complexity. Therefore, probabilistic methods to determine the tolerance chain should be applied [7].
Under the premise of a normal distribution of each individual tolerance the common method of Root-Sum-Square-Calculation (RSS) is applied [9]:

$$T_{RSS} = \sqrt{\sum_{i=1}^{n} {t_i}^2}$$

T_{RSS}	sum of the tolerance chain
t_i	tolerance of component i

The key characteristic vertical section diameter (missing link of the chain in figure 3) can be estimated by the root sum square (RSS) of all link tolerances. Experience has shown that genuine tolerance values are closer to the result of the RSS-method than to the Min-Max- method. [10]

5 System optimization

In some cases the analysis of the tolerance chain or the experience with the assembly process shows that the allowed functional tolerance does not lead to a stable assembly result. There are two options to solve this problem. The first option is to replace the equipment with one offering higher accuracy. But this goes hand in hand with higher equipment costs. Optimizing only the critical parts of the system based on the tolerance chains' analysis is a smarter option.

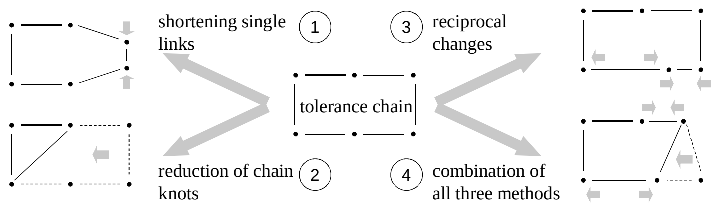

Fig. 4: Methods for optimizing the tolerance chain

Figure 4 shows four possibilities to optimize a tolerance chain. Shortening single links (4, 1) means to reduce process deviations or uncertainties. Also the number of chain-knots can be reduced (4, 2) by using an additional measurement system. Reciprocal changes (4, 3) are an option, if the shortening of one link does not increase costs that much, and the extension of another link safe a lot of investment. The combination of all three methods (4, 4) generates maximum savings.
Another important aspect of the tolerance chain method is that the user is forced to consider all factors of the assembly process, which contribute to a deviation in the product. This ensures that the entire tolerance chain is examined and only those variables are changed, which will optimize the cost-benefit ratio [11].
This is the theoretical approach to benefit from the referenced tolerance chain analysis combined with a system optimization. Figures 5(a,b) shows the assembly of a miniature slab-lense marking laser (micro-slab). The task is to position several lenses in a specific order to achieve an optimal Performance Key Characteristic "Quality of the Laser-beam". The same process is shown in both figures 5(a,b), but different equipment is used.
Figure 5(a): A robot with a gripper places an optical component (lens) on the laser base plate. The base plate is fixed on a work piece carrier on the installation surface. To program the referenced process offline, the relative positions of the robot, the assembly equipment and the location of the base plate on the installation surface have to be determined in advance. For the positioning of the optical component the accuracy of the robot is important. Only if the component can be supplied in the required quality, the assembly process is feasible. These influences are shown in the tolerance chain below. [12]
The system optimization can be executed in several steps to cut down the long tolerance chain. With the help of the system identification, the individual tolerance chain links can be shortened by metrologically identifying the existing values without using the manufacturing and assembly tolerances. Accuracy can also be enhanced during the ongoing process by using system identification.

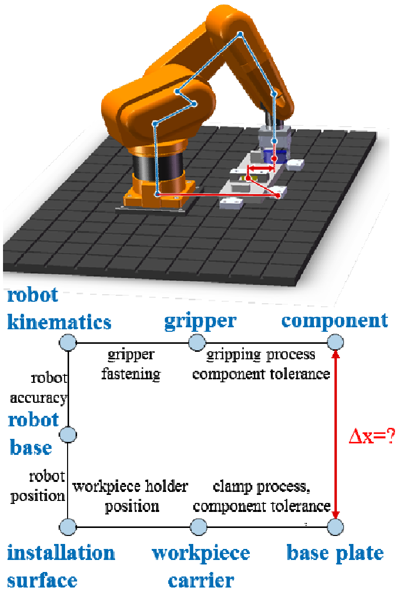

Fig. 5(a): Assembly of a slab-lens marking laser [12]

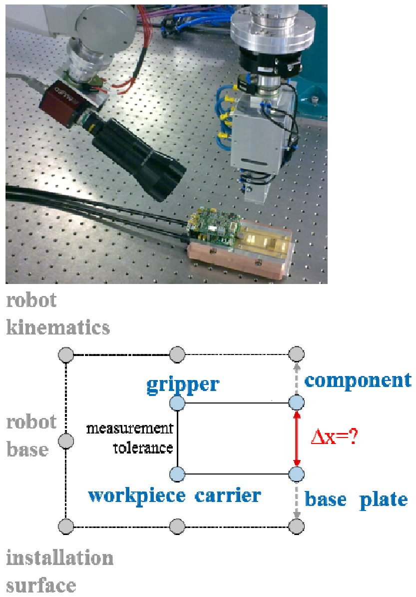

Fig. 5(b): System optimization by shortening the tolerance chain [12]

Figure 5(b): In the following, three ideas for shortening and optimizing the referenced tolerance chains are presented.

The first idea is the integration of an additional vision system which determines the position of the optical component inside the gripper after each gripping process. The location of the base plate can also be inspected before positioning the component and therefore be included in the path planning. Thus, during the process the conditions for part and assembly tolerances are replaced by only one condition, i. e. measurement uncertainty. In some cases, the accuracy of the system may not be enough and the process can not be realized as required. Besides the system identification, there still exist additional possibilities to achieve a further optimization of the system.

For idea two an in-line measurement is used to monitor the robot-position during critical processes in order to compensate possibly occurring position errors that are not modeled in advanced. Thus, the condition describing the position of the robot, is replaced by a more specific one that describes the measurement accuracy of the in-line measurement system. The accuracy of the robot itself only has a minor influence on the system. A positive side effect is that less precise robots can be used which are considerably cheaper than high-precision designs. If the increase of accuracy through system identification and inline measuring does not lead to the required quality, the assembly process needs to be changed.

The third idea is to use the product itself within the operation during the assembly process. As a result, the quality of the product’s features can be controlled immediately. The idea is to place sensors as an adjustment mechanism in the product. Upon commissioning, the product’s features can be adjusted immediately. This process will completely eliminate the influence of the assembly equipment and reduce the tolerance chain to a minimum. The tolerance chain, as described in the third idea, is shown in figure 5(b) [12].

6 Conclusions

In practice it is observed that, in order to achieve functional tolerances, complex assembly processes are planned, independent of the product's size and costs. This paper shows that a consistent tolerance management will ensure a defined installation process, thus an efficient implementation can be performed and the desired functionality and quality of the product will be achieved. This planning process allows a noticeable reduction of the start-up time after a product changeover and therefore enables a more economical automated assembly. The concepts of tolerance management hold true independent of product size or the industry branch.

Additionally, a strong tolerance management provides the user with a better understanding of the assembly system, as certain parameters are known in advance, which again is helpful for further production processes. In particular for reconfigurable and flexible assembly systems an exact planning is absolutely necessary to achieve short commissioning times and to guarantee an error-free product launch. The main methods of "Product Analysis", "Product Design", "Process Analysis" and "System Optimization" guide the user towards a strong assembly systems' tolerance management in every branch of global industries.

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