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DEVELOPMENT OF A TOLERANCE CONCEPT FOR THE OPTIMIZATION OF A WORM GEAR

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Abstract: *In mounting, the assembly of parts or groups to products or to groups of higher levels takes place in the production. It usually forms the end of the operational value chain. Thus, the assembly occupies a key position regarding the realization of the characteristics of the products or modules, because in this case it represents the last opportunity to influence the features and their qualitative variety. When functional products or modules are mounted, the achievement of the intended function in the desired quality is a major priority. It depends essentially on the assembly processes. The convenient setting of the assembly process can be found by considering and weighing it from different perspectives. This work discusses the problems of tolerance and places them in the foreground. The tolerances of the components of the product, the tolerances of the arrangement of the components to each other and the tolerances, measurements, and adjustments involved in the process of assembly are taken into account. The aim is to create optimization strategies based on the analysis of influencing factors of the component tolerances and the assembly process.*

Key words: *tolerance, key characteristics, tolerance chain, assembly.*

1. INTRODUCTION

In order to provide the required product characteristics in assembly, functional tolerances are specified in the design of a product. Tolerances need to be defined so that the desired measurement can be achieved in any industrial processes. The definition of tolerances is a compromise between the functionality of a component and the manufacturing cost. From the perspective of assembly the product tolerances represent specifications or restrictions that limit the feasible solution space in the assembly planning. The viable tolerances in the planned installation process in turn restrict the allowable solution space in the design. Consequently, there are tolerance-related interactions between the product, the particular assembly process and the resources resulting from the assembly process.[1] Since tolerances have a significant impact on the cost of the installation, a detailed analysis of the tolerance problem in the design of assembly systems is necessary.[2]

2. MOTIVATION

The paper discuss the development of technology for substitution of bronze (CuSn12Ni) from worm gear by a low alloy steel. Since the use of a steel-steel pairing eliminates the properties of the soft bronze material. Furthermore, by the use of the steel-steel-pairing there is no possibility for the worm wheel to running in. Thus can not be compensated the manufacturing and assembly tolerances. An alternative solution must be found to guarantee the function of the worm gear in the desired quality.

Sub-goal of ZeMA is the substitution of bronze (CuSn12Ni) from worm gears by using appropriate man-

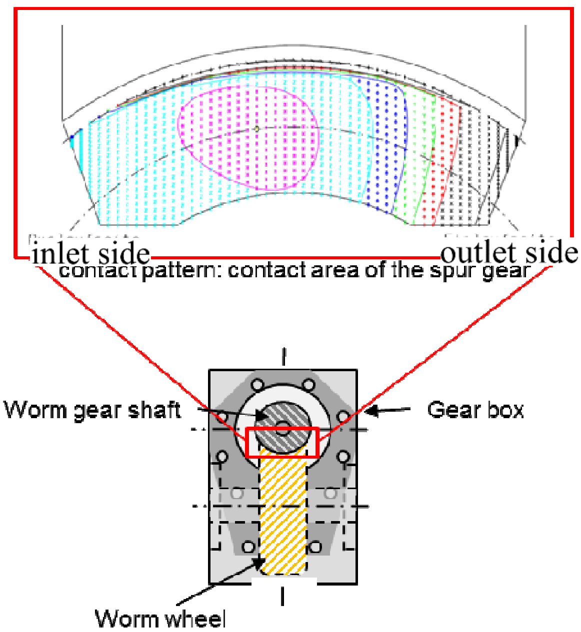

Fig. 1. Contact pattern of a worm gear.

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ufacturing and assembly tolerances. Since this is difficult to grasp and the need for the selection of suitable tolerance ranges cannot be mirrored on the product alone, further tracking of the features is necessary to identify the customer's requirement. The optimization of the wear pattern was selected to test, because factors such as structure and location of the wear pattern are very sensitive to changes in the tolerance ranges. The wear pattern occupies a defined position on the tooth flanks. In addition, the shafts must be aligned to the gear box, which is why the gear box is the reference size of the system. The functional tolerances ensure that the required contact pattern can be achieved, visible in Fig. 1 This must be ensured by mounting tolerances.

3. PROCEDURE FOR ANALYSIS, EVALUATION AND DETERMINATION OF THE ASSEMBLY PROCESS

The interactions described in section 1, starting from a customer requirement, are shown in Fig. 2 The Figure illustrates the interactions between product, assembly process and resources and serves as a tool for the procedure of determination and optimization of an assembly system. The present work develops optimization strategies in relation to the tolerance management, which are used to design an assembly process by a consideration of function-related tolerances. For this purpose the mounting process is designed for an efficient implementation of the product in the desired quality. The procedure is intended to support early consideration of the tolerance issue in the product development process.

The customer's requirement forms the basis of the approach. Based on this information, the approach must be used not only for the product alone but overall for product, process and equipment. In the first step, the product analysis is performed. Here, precedence has to be created and the product specifications must be developed. A large number of tolerances and characteristics for the manufacturing and assembly processes can be obtained at a very early stage of the process. Not all tolerances are important for each step in the assembly, which is why the most important tolerances in the assembly process have to be identified. These tolerances are called key characteristics (KCs) and can be determined by using the method of key characteristic Flow-Downs.[3] The next step is the product design, an iteration step to question and improve the revised result. This step can be repeated as often as necessary according to the customer's requirements. In the following step, the resource is created or optimized. This requires a visualization of the process to detect the variations in the mounting process. The tolerance chain is a comprehensive tool to visualize tolerance problems in the analysis process. The method of the tolerance chain is used to identify the potential of optimization of worm gears by eliminating the inlet by using suitable tolerances. For a better process overview, the worm gear is split and displayed into several planes (Fig. 6). Iteration is performed by system optimization. Now, there are three ways to optimize a tolerance chain. The shortening of the individual tolerances reduces process variations or uncertainties.

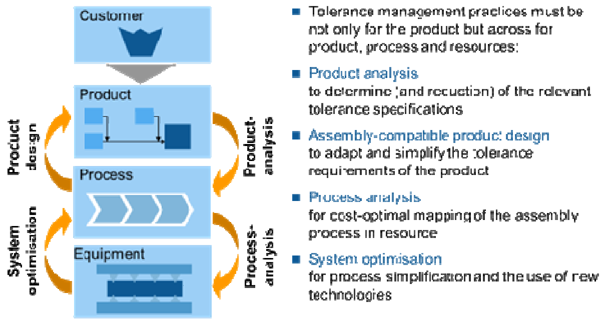

Fig. 2. Procedure for analysis, evaluation and determination of the assembly process [4].

Another option could be the mutual changes in the tolerance chain, if the costs are not significantly increased by the shortening of a chain link, and the extension of another chain link saves major investments. The combination of all three methods generates maximum savings.

4. METHOD OF TOLERANCE CHAIN

The method of the tolerance chain is used in this paper to identify the potential of optimization of worm gears by eliminating the inlet by using appropriate tolerances. Previous research has not yet managed to establish a steel-steel mating in worm gears, which is mainly due to frequent incorrect positioning in the joining processes. To identify all deviations in the processes and analyze possible causes for the inaccuracy tolerance chains of all levels were identified. By comparing the individual levels the potential of improvement by streamlining and shortening the tolerance chain was demonstrated.

Fig. 3 shows different methods to streamline and shorten a tolerance chain. According to the first method, a tolerance chain can be shortened by reducing individual members (Fig. 3, No. 1). The tolerance chains shown in Fig. 3 can be reduced, for example by a more precise fixation of the work piece in the work piece carrier. Further, a tolerance chain can be shortened by reducing the number of elements (Fig. 3, No. 2). A reduction in the tolerance chain can also be achieved by a joining aid. In order to increase the efficiency of tolerances in compliance with the target tolerance of the chain a reciprocal change of the individual members can be useful to reduce uncertainties (Fig. 3, No. 3). This is approximately the case when the reduction of one limb is connected to a relatively low cost, while the extension of another is associated with relatively high cost savings. The combination of the three methods listed leads to change in the efficiency of the tolerance chain. In addition, tolerance chains can be a basis for interdisciplinary discussions by offering the possibility of a simple visualization of deviations [5].

5. FACTORS INFLUENCING THE CONTACT PATTERN

Before the key characteristics of the product can be identified, knowledge of the components that influence the contact pattern is required. Since the engagement of gears generally does not cause the contact of the edge

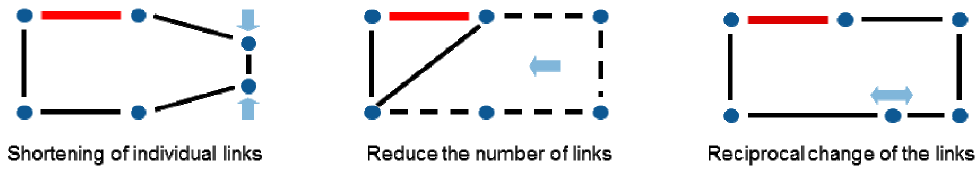

Fig. 3. Methods to shorten a tolerance chain [6].

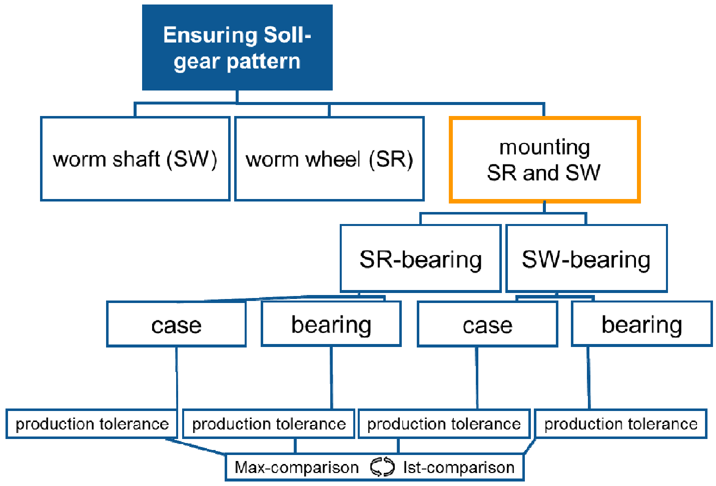

Fig. 4. Factors to determine the contact pattern

over the entire surface, the force is transferred only onto a partial area of the tooth surface, which is visible on the image carrier.

The factors that influence the bearing size and contact pattern position can be derived in Fig. 4. The main reason for location and severity of the contact pattern on the tooth flank are manufacturing tolerances and tooth geometry of both the worm wheel and the worm shaft. These differences are relevant for the tolerance chain analysis performed in section 8. The incorporation of components to one another is important. Since the case is the reference imaging size of our system and the position of the two waves to each other is important all deviations resulting from manufacturing and assembly inaccuracies, starting from the case, must be taken into consideration to the desired contact pattern. For this, the case was measured by a coordinate measuring machine. This data was then compared with existing values of the technical drawings. In addition to the maximum values of the tolerances, the worst case, it is possible to use the actual values towards the analysis.

6. IDENTIFICATION OF THE KEY CHARACTERISTICS

The worm gear has a considerable number of tolerances that are not all relevant to the function.[7] The deviations of the ribs in the case, for example, might be irrelevant to the function. For this reason, the tolerances that are relevant for the function of the product and that must be considered during installation planning were determined according to the approach elaborated in section 3.

In the next step of the method to identify KCs, product KCs should be identified based on the product features determined in the second step. As explained in section 3 it should be assessed whether the deviations occurring in the production process of each product feature are critical to meeting customer demands. These deviations likely to be encountered in the production process need to be compared with the maximum permissible deviations, which are determined by the customer demands. When identifying the product KCs, it is important for the assembly process planning to consider only those product characteristics that are also affected by the installation process.[8]

In a joint workshop with the Laboratory for Machine Tools of the RWTH Aachen (WZL) and the Ruhr-University Bochum (RUB) the following key characteristics were identified:

- distance of axles
- axial movement
- cross angle of axles

Furthermore, only those product characteristics that are important for the fulfillment of customer demands should be considered. For all three product characteristics it was assumed on the basis of expert knowledge from ZeMA, WZL and the RUB that compliance with the permissible deviations due to the production-related variations in product characteristics is critical. The three product characteristics meet the criteria for the product KCs.

7. APPROACH FOR IDENTIFICATION OF PROCESS-RELEVANT PARAMETERS

In order to determine all process-relevant parameters distinctly in the x-, y-, and z-direction, two levels per-

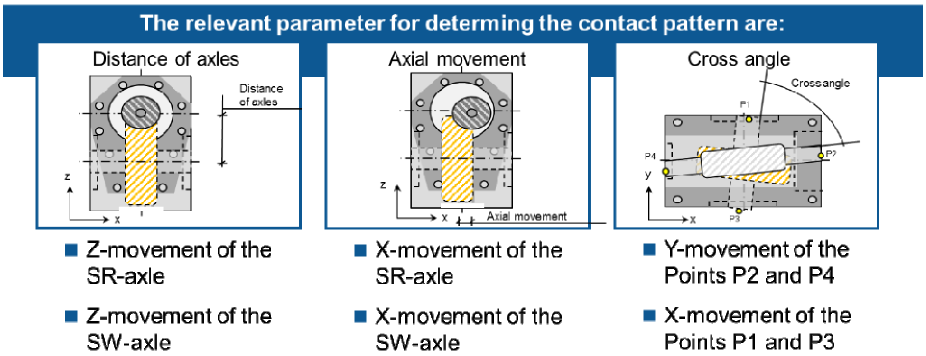

Fig. 5. Key characteristics to determine the contact pattern.

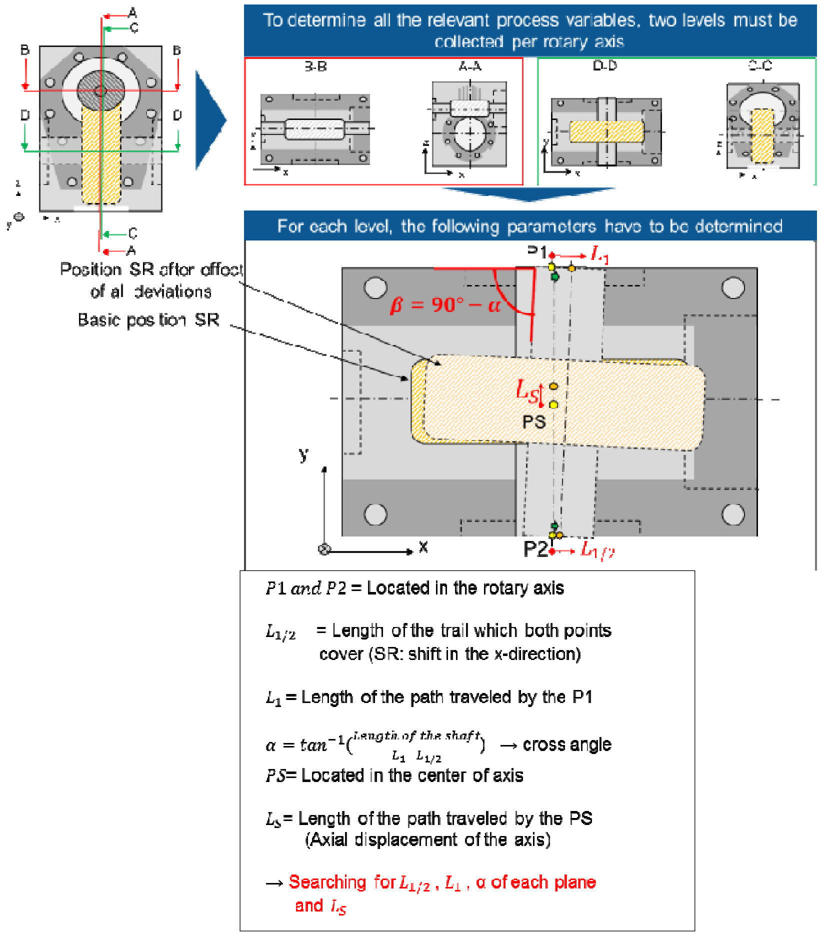

Fig. 6. Procedure for determination of all relevant process variables.

pendicular to each other are drawn in the axis of rotation of each shaft, the worm wheel and the worm shaft. By this measure each shaft can be clamped in two levels. Fig. 6 also shows the procedure for determination of the parameters (for example, section DD). First, the points P1 and P2 are placed in the rotational axis of the original position of the worm wheel. The deviations are allowed to flow to the points that are relevant to the displacement of the points in the x-direction.

Based on the tolerances of the case and the mounting of the shaft, there is a displacement of the points in positive x-direction. The range of this distance differs in most cases, due to different tolerances cases in the two points different, so that the points move to a different-sized track in said direction. The distance that both P1 and P2 cover is referred to as $\boldsymbol{L_{1/2}}$ in Fig. 6. This distance is the same as the displacement of the worm wheel in the x-direction. The distance $\boldsymbol{L_1}$, however, is the distance of the point that covers the greater distance. In Fig. 6 this is P1. With the knowledge of the two routes, $\boldsymbol{L_{1/2}}$, the distance $\boldsymbol{L_{1/2}}$ and the length of the axis the axis intersection of the plane can be determined. To determine the track of the axis in the y-direction an additional factor is required: the track $\boldsymbol{L_S}$. To determine this range point PS is placed at the center of the worm wheel at the origin. The distance the point PS has completed under influence of all deviations in the y-direction is referred to as $\boldsymbol{L_S}$. This distance also describes the displacement of the worm wheel in the axial direction. By doing so, all of the parameters can be determined and the tolerance analysis and key characteristics can be set.

8. TOLERANCE CHAIN ANALYSIS OF THE WORM GEAR

In the following section, the procedure introduced in Chapter 6 will be carried out for each plane described in Fig. 6.

8.1. Tolerance chain analysis of the worm wheel in the x-y plane for the detection of α and $L_{1/2}$

For possibly occurring deviations in the x-y plane of the points P1, P2, and PS, the following deviations shown in Fig. 6 are relevant:

1. Deviation (case − bearing-SR):
Reference lowercase size and starting point of the analysis is the case. This must first be used towards the deviation of the positioning of the hole to the symmetry axis and the manufacturing tolerance of the hole for mounting of the shaft. The deviation of the fit is a part of the analysis. Furthermore, the ball bearing is pressed with the case. Finally, the tolerance of the outer diameter of the bearing must be used towards the tolerance analysis.

2. Deviation (bearing-SR − worm shaft):
The deviation 2 includes the radial clearance and the manufacturing inaccuracy of the inner ring of the bearing. In addition, the type of the joint, the fitting and the manufacturing inaccuracy of the shaft of the worm wheel are relevant for computation.

3. Deviation (worm shaft − bearing-SR):
The radial play of the second bearing is relevant for this deviation. Manufacturing tolerance of the inner ring and the tolerance of the fit of the bearing play are important for this variation.

4. Deviation (bearing-SR − recording storage):
The second bearing is pressed by a fit into the cover. This cover serves as a receptacle of the worm wheel and is then screwed to the case. If this recording of the camp is not in the position intended by the technical drawing, this manufacturing inaccuracy must be used towards the tolerance chain. Furthermore, this recording and the outer ring of the bearing are subject to a manufacturing inaccuracy.

5. Deviation (location bearing − location cover):
First, the bore for receiving the bearing must be checked for its position and manufacturing variations. Both tolerance dimensions must be used towards the analysis. In addition, the deviation of the outer bearing ring as well as the fit between the receptacle of the bearing and the bearing itself need to be taken into account.

6. Deviation (location cover − case):
The inclusion of the cover is based on a fit. Additionally, deviations resulting from manufacturing inaccuracies of the cover and the case must be counted towards the analysis.

Using these deviations, the tolerance chain shown in shown in Fig. 7 was constructed.

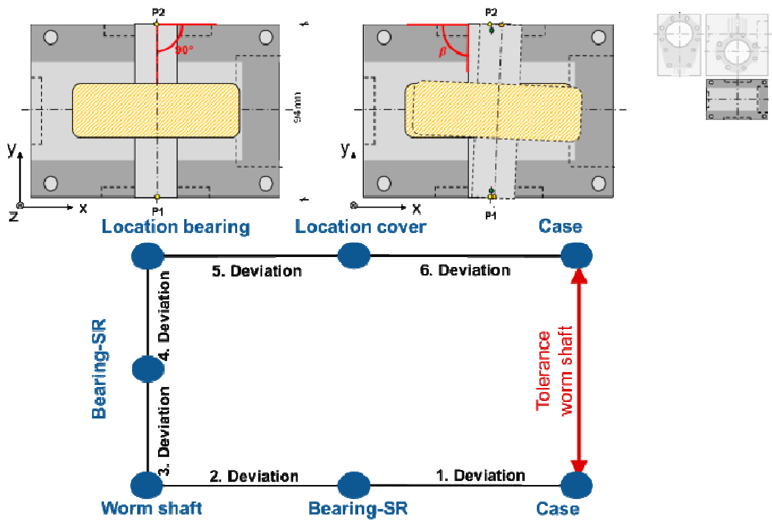

Fig. 7. Tolerance chain analysis of the SR in the x-y plane for the detection of α and $L_{1/2}$

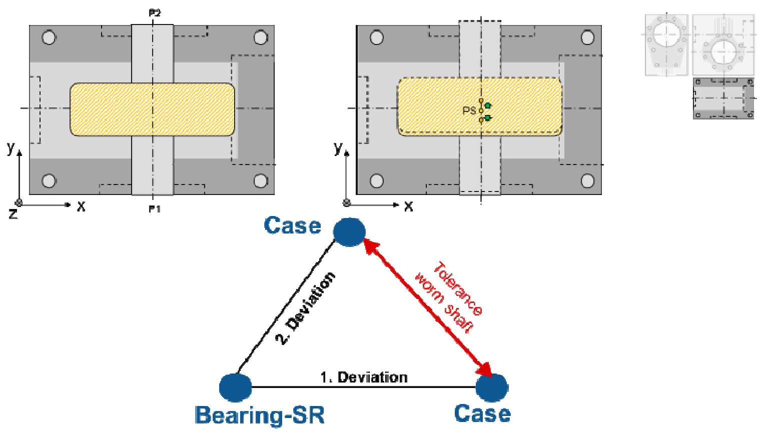

Fig. 8. Tolerance chain analysis of the SR in the x-y plane for detection of L_S.

The calculation of the resulting deviation of the tolerance chain of the worm wheel in the x-y plane can be carried out with the aid of the worst-case method.

In the application of the worst-case method the individual maximum deviations have to be added in order to determine the resulting total deviation. Thus, both the maximum values for the resulting displacement of the worm gear in the x-direction, $L_{1/2}$, and the maximum axis intersection, α_{max}, can be determined. In addition, a value for α_{ist} was determined on the basis of the measured deviations of the worm wheel in the x-y plane. Since the displacement of the worm gear in the x-direction in this plane has no effect on the contact pattern, it needs to be considered separately. This means that the displacement of the worm wheel in the y-direction, the displacement of point PS in the axial direction, has to be determined.

1. Deviation (case − bearing-SR):

The manufacturing inaccuracy of the case bore for receiving the bearing is included in the first deviation. Since the displacement of the shaft in the axial direction is to be determined here, it is not the position of the hole.

2. Deviation (bearing-SR − case):

Here, the deviation of the axial play of the camp, as well as the manufacturing inaccuracy of the wave in the y-direction, is important. In addition, the manufacturing inaccuracy of the bearing width must be included in the analysis.

In this example the worst-case method was used. Accordingly, the resulting displacement of the worm wheel was calculated in the y-direction.

8.2. Tolerance chain analysis of the worm wheel in the y-z plane for the detection of α and $L_{3/4}$

Fig. 9 shows the worm wheel clamped in the y-z plane. The axis intersection angle α and the displacement of the worm gear in the z-direction are to be found. For this, two points are placed in the axis of rotation of the worm wheel and the displacement of the points in the z-direction, caused by the manufacturing and assembly inaccuracies, are determined. The tolerance chain analysis of this plane coincides with the plane of the x-y plane. The background is the same tolerance specification in the engineering drawing of the case with respect to the entrance hole in the shaft. In the technical drawing, a similar degree of tolerance with respect to the position of the bore is specified for both the bottom of the case, reference surface 1, and the side surface of the case, reference surface 2. In this analysis, the values for the bearing clearance, the fits and the manufacturing inaccuracies of the shaft and the case are also equal. The values for the calculated maximum axis intersection angle and the maximum displacement of the worm wheel in the z-direction are identical with those of the x-z plane.

8.3. Tolerance chain analysis of the worm shaft in the x-y plane for the detection of α and $L_{5/6}$

Below, a tolerance chain analysis of the worm shaft in the x-y plane is performed (Fig. 10). The deviations are relevant for the displacement of the points in said plane:

1. Deviation (case − bearing-SR):

First, the position of the hole and the production accuracy of the bore are checked and entered into the tolerance chain. Next, the manufacturing accuracy of the bearing outer ring and the tolerance of the fit must be included in the calculation of the first variation.

2. Deviation (bearing-SR − worm shaft):

The production tolerance of the diameter of the bearing inner ring and the shaft, the radial clearance and the fittings are factors that must be considered in the second deviation.

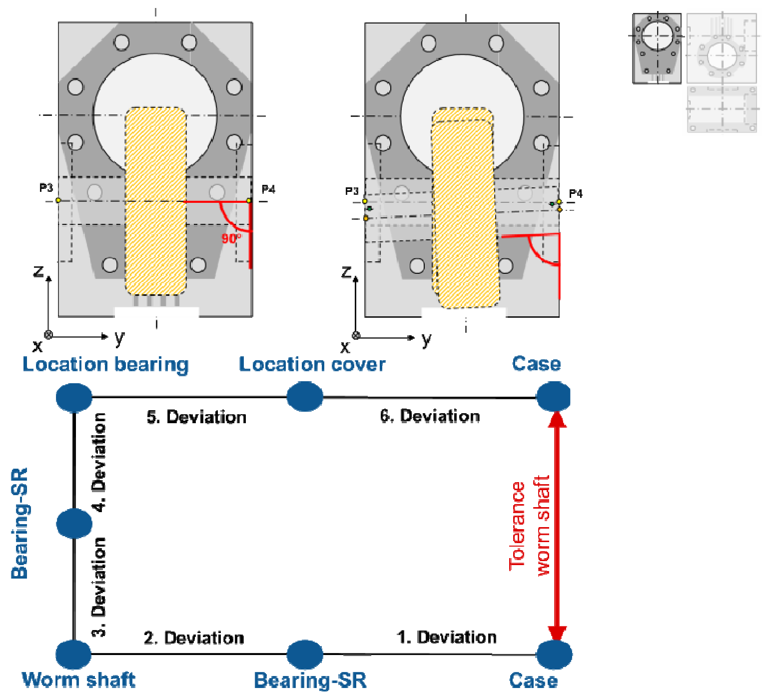

Fig. 9. Tolerance chain analysis of the SR in the y-z plane for the detection of $L_{3/4}$

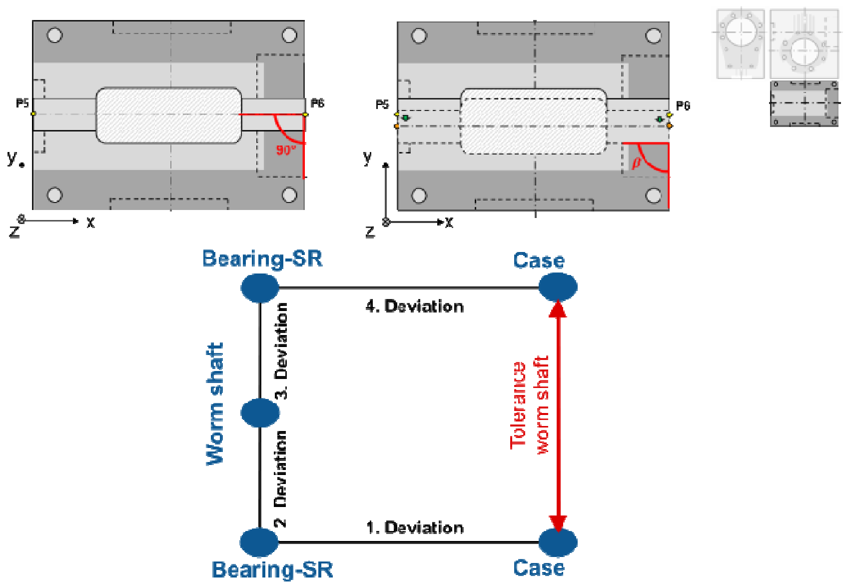

Fig. 10. Tolerance chain analysis of the SW in the x-y plane for the detection of $L_{5/6}$ and α.

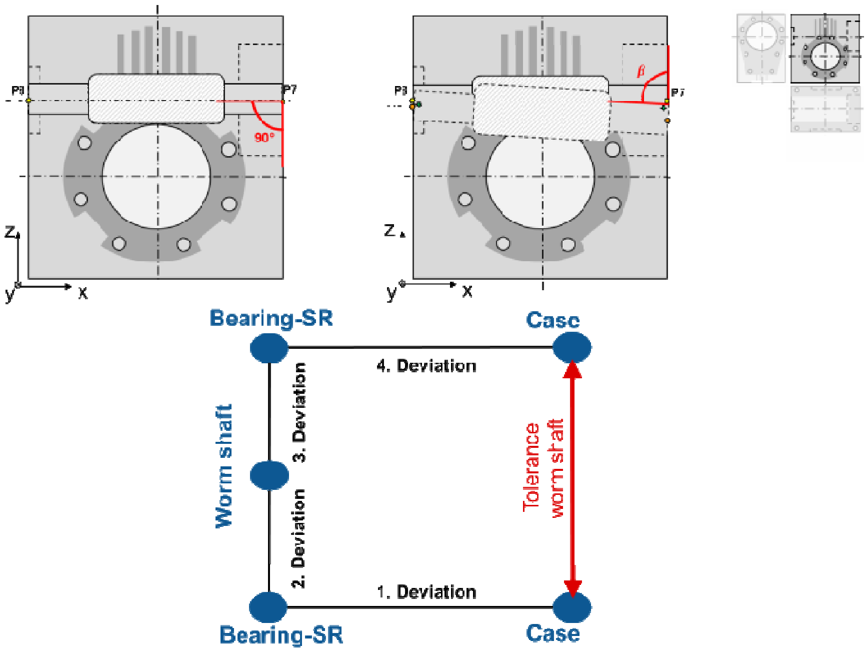

Fig. 11. Tolerance chain analysis of the SW in the x-z plane for the detection of $L_{7/8}$ and α.

3. Deviation (worm shaft − bearing-SR):
Again, the manufacturing tolerances of the bearing inner ring and the shaft as well as the bearing clearance and the fits must be considered. The technical drawings of the case serve as the source of the tolerance ranges.

4. Deviation (bearing-SR − case):
The difference between the bearing and the case results from the manufacturing tolerance and the position of the hole, the manufacturing tolerance in diameter of the outer ring of the shaft, as well as the fit between the two components.

The calculation of the resulting deviation of the tolerance chain analysis of the worm shaft in the x-y plane can be performed by using one of the methods introduced in chapter 7:

Again, the maximum total deviation has to be calculated by using the worst-case method. The resulting displacement of the worm gear in the x-direction $L_{5/6}$ and the maximum axis intersection angle α_{max} were determined here.
In addition, a value for α_{ist} was found on the basis of the measured deviations of the worm shaft in the x-y plane.

8.4. Tolerance chain analysis of the worm shaft in the z-x plane for the detection of α and $L_{7/8}$

In the further course, a tolerance chain analysis of the screw shaft is performed in the x-z plane (Fig. 11). For the displacement of the worm shaft in the z-x plane, the following deviations are relevant:

1. Deviation (case − bearing-SW):
First, the manufacturing inaccuracy of the hole must be incorporated in the tolerance chain. Further, the manufacturing accuracy of the bearing outer ring and the toler-

ance of the fit must be included in the calculation of the first deviation.

2. Deviation (bearing - SW − worm shaft):
Important are the production tolerance of the diameter of the bearing inner ring and the shaft, the radial clearance and the fittings are factors to be considered in the second deviation too.

3. Deviation (worm shaft − bearing-SW):
Again, the manufacturing tolerances of the bearing inner ring, of the shaft, the bearing clearance and the fits must be considered.

4. Deviation (bearing-SW − case):
Important for this are the difference between the bearing and the case results from the manufacturing tolerance and the position of the hole, the manufacturing tolerance in diameter of the outer ring of the shaft, as well as the fit between the two components.

9. SUMMARY AND CONCLUSION

In the present work, a tolerance concept has been developed, which allows the design of an assembly process already at an early stage in the product development process by a consideration of function-related tolerances. Thus, an efficient implementation of product functions with the required quality is guaranteed.
First, the fundamentals and the state of the art of assembling and the tolerances are shown. Those factors that have an impact on meeting the requirements for the realization of the product features were analyzed. The juxtaposition of the influencing factors of the component tolerances and assembly process showed that the influence of the factors is largely dependent on the structural design of the connections between the parts of the product.

On the basis of one of these influencing factors the case of the worm gear was split into different levels, and it was checked whether the tolerances taken into account could be observed. The identification and analysis of the alternatives are supported by a visualization of the tolerance chain. This visualization serves to promote the discovery of ways to reduce the tolerance chains.

The elaborated procedure was applied using the example of a worm gear. In this case, the derivative of the tolerances of the customer demands, which are to be considered in the design, proved to be extremely useful. This is because the amount of tolerances to be taken into account and thus the effort necessary in the analysis was significantly reduced.

Moreover, the visualization of tolerance chains undertaken in the framework of the second step proved to be advantageous. Thus, some ways to shorten the tolerance chains could be identified with the help of visualization. The creation of tolerance chains and the carrying out of the necessary calculations was very time consuming. To reduce the time required supporting software is likely to be helpful. Since the probability that the individual deviations of the tolerance chain analysis will always take their extreme values is usually very low, further transmission must be measured to be able to make a conclusion about the existing values of the axis intersection angle and the center distance. Furthermore, the values of the determined key characteristics must be passed to the RUB and the WZL. With the help of both partners, the influence of this parameter can be determined on the contact pattern and the need for adjustment feature of the worm gear can be clarified.

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