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COMPUTER-BASED AND EXPERIMENTAL VALIDATION OF AN APPROACH TO COMBINE TOLERANCE ZONES WITH ELASTIC DEFORMATIONS

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ABSTRACT

This article will introduce the computer-based and experimental validation of a method taking elastic deformations into account in the computation of tolerances. Especially the numeric and experimental validation process is highlighted in the paper. In order to be able to take elastic behavior and part deviations into account simultaneously an approach has been developed to achieve this. As it is a mandatory task to validate the approach different methods were exerted and compared. So it is possible to show the adequacy of different methods used and particularly the benefit of taking the elastic behaviour of assembly components into account regarding the results of common rigid-body CAT tools.

Keywords: tolerance analysis, elastic deformations, experimental validation, simulation techniques

1 INTRODUCTION

In order to reduce manufacturing costs like rework, scrap or further cost-intensive activities like warranty or product liability claims and recalls it is important to design components and products that are robust to process variation resulting from the manufacturing process [1]. Methods like statistical tolerance calculations based on the Six Sigma quality initiative or two and three dimensional computer based tolerance analysis (Computer Aided Tolerancing CAT) can help to design products robustly. The requirements of reducing production costs in early stages of the product development process can be satisfied applying CAT analyses based on statistical test data [2] but still has to be improved.

So the analysis of tolerance chains, production variations and assembling variations can be considered as state of the art. By the use of these simulation methods, which are based on statistical procedures, predictions according to the assemblability of rigid bodies can be computed. In real technical problems not only simply tolerances have an influence on the assemblability and on the technical function of the system, also the elastic behaviour of the system has to be addressed. The elastic behaviour of a part within its application can be influenced by internal and external forces and temperature for example. Imagine the following example resembling a one-dimensional stack-up problem [3] (Figure 1a). The stacked blocks of different dimensions with an applied tolerance of ±1 mm/±2 mm have to be placed in a u-shaped and – for demonstration purposes – ideal part. A manual or computer based analysis of this assembly with rigid parts would result in a predication about the resulting gap s. The result reveals whether the parts will be assemblable or not and what gap will be there. Furthermore statistical information about the expected amount of groups able to compose can be obtained. Regarding the process of assembling and its forces or a force F resulting from the operating conditions of this group of components (Figure 1b) one can deduce that there are important coherences concerning the resulting gap if taking elastic deformations and part deviations into account simultaneously.

Regarding this example the need of robust, easy to use simulation techniques can be deduced. The following sections describe the application of the developed method considering these effects in order to improve the adequacy of tolerance analysis results in a validation process.

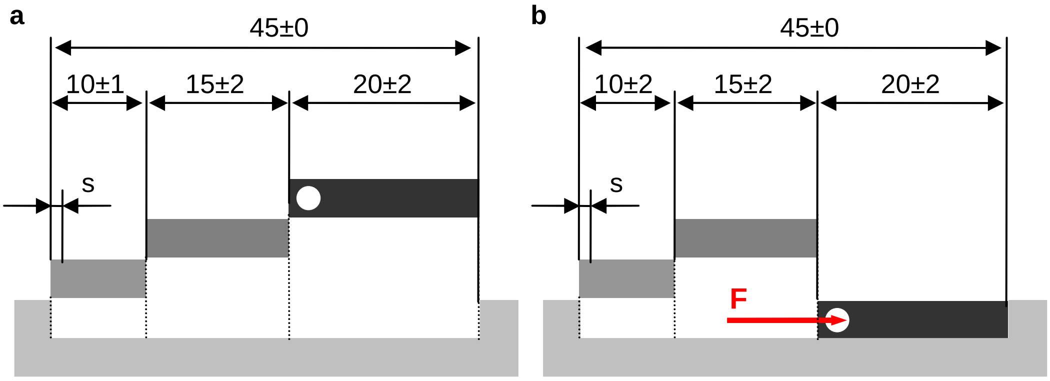


Figure 1. One-dimensional stack-up problem

2 STATE OF THE ART REGARDING TOLERANCE ANALYSIS

Simulation tools provide functions to perform a CAT analysis of more-dimensional tolerance chains under form-, positional- and dimensional deviations. But in tolerance analysis systems the tolerance stack-up is simply modelled with rigid bodies which are assembled without any stress. These commercial systems provide different analyses to obtain information on the main contributors to an assembly deviation and statistical results like Monte Carlo Simulation, Sensitivity Analysis or High-Low-Median Analysis or GeoFactor Analysis. These analysis tools are nowadays widespread tools in industrial applications.

Methodologies modeling the assembly process of compliant parts are proposed in various publications but mainly focus on welded, riveted or bolted assemblies [4]. Sellem an Rivière [2] for example propose a mechanical approach for this problem focusing on welded, riveted, bolted or glued parts based on the computation of influence coefficient matrices for use in process-related specifications and tuning phases. Also Liu et. al. [5] propose a mechanistic variation model using the method of influence coefficients focusing on the assembly process. Finite Elements Analyses are used to derive a stiffness matrix in most cases [2], [6], [7], [8] but not to determine the interaction of forces resulting from product usage and geometric deviations. All of these methodologies focus on either Monte Carlo Simulation or a statistical Finite Element Analysis (FEA) or other statistical representations (e.g. [9]) in order to predict deviations for the assembly or the assembly process of compliant parts. Especially the estimation of residual stresses and springback in compliant assemblies are focused [10]. Furthermore the assembly process but not the general influence of compliant parts in product usage or operation is taken into account. The authors Samper and Giordano also describe the need for coupling elastic behaviours due to external loads with geometrical variations and propose a method for linking models of rigid imperfect models with flexible perfect bodies model using a kinematical closing loop [11]. Moreover the necessity for validating a proposed method using measurement data is outlined in [7] in detail.

3 INTEGRAL TOLERANCE AND ELASTICITY ANALYSIS

A specific concept (ITEA) has been developed and continuously improved to take elastic behaviour into account using the functions provided by common CAT tools and the Finite Elements Analysis [12], [13], [14]. The method is on one hand based on a mathematical representation of technical, deviation-afflicted surfaces and an FEA on the other in order to acquire data for the impact of forces. In order to describe the surfaces with their deviations and elastic deformations correctly a superposition for each contact surface has to be performed [14]. The two resulting representations for the mating contact can be combined with a phase parameter for the assembly variants. Based on these results a calculation of the four statistical moments (mean value, standard deviation, skewness and kurtosis) can be performed in order to receive a statistical description useable for standard, Monte Carlo-based simulation [13], [14] (see figure 5). The major advantage of this procedure is that it is universally applicable und hence has the advantage that no additional software or specific CAD, FEA or customized CAT applications are required.

4 THE VALIDATION PROCESS

In order to show the possible applications of the method and its precision a validation process for the proposed method has been performed. Considering the features and simulation types/techniques of available software packages a specific model is built up to serve as a common basis for comparing the proposed method with common CAT tools but also experimental tests. The valuation concept shown in figure 2 is set up for this comparison. It is described in detail in chapter 4.2.

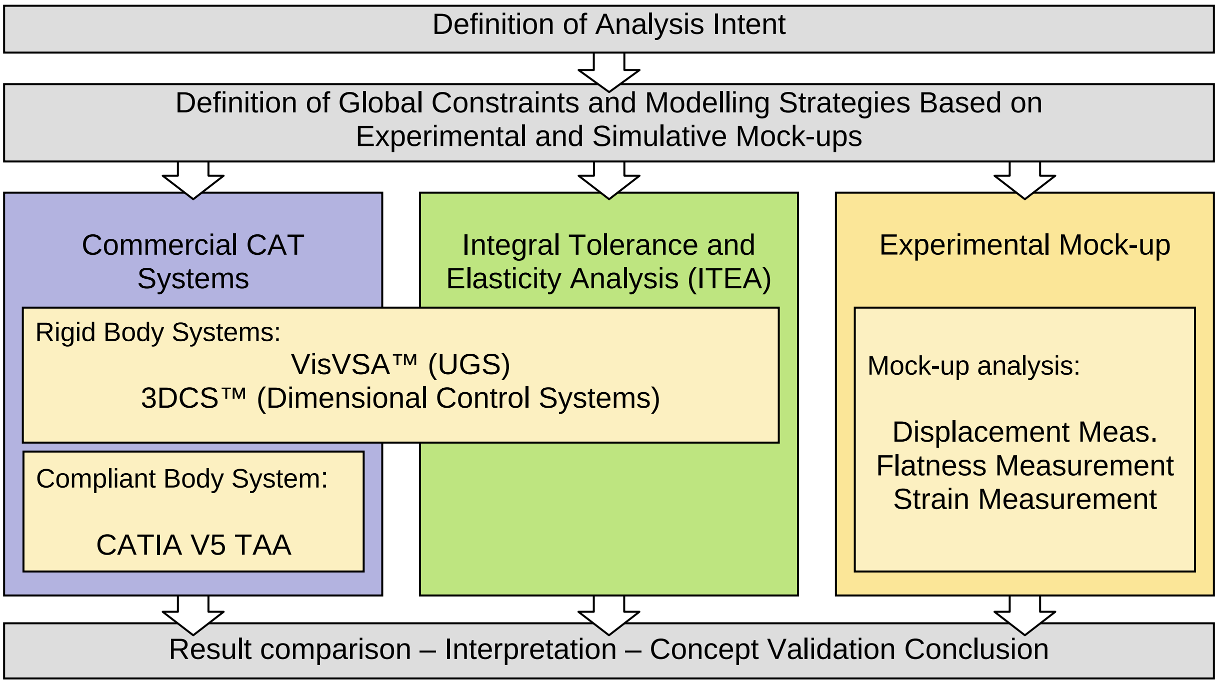


Figure 2. Evaluation concept

4.1 The model and its prototype

A simple sheet metal assembly connected by spot welding was used to show the impact of deviations caused by the manufacturing processes of the sheet steel and the weldment and the elastic behavior of the sheet metal itself. The assembly consists of two parts and it is assembled using a clamping fixture (figure 3). The fixture ensures that the parts are aligned correctly and that an elastic deformation arises during the process of welding at two positions.

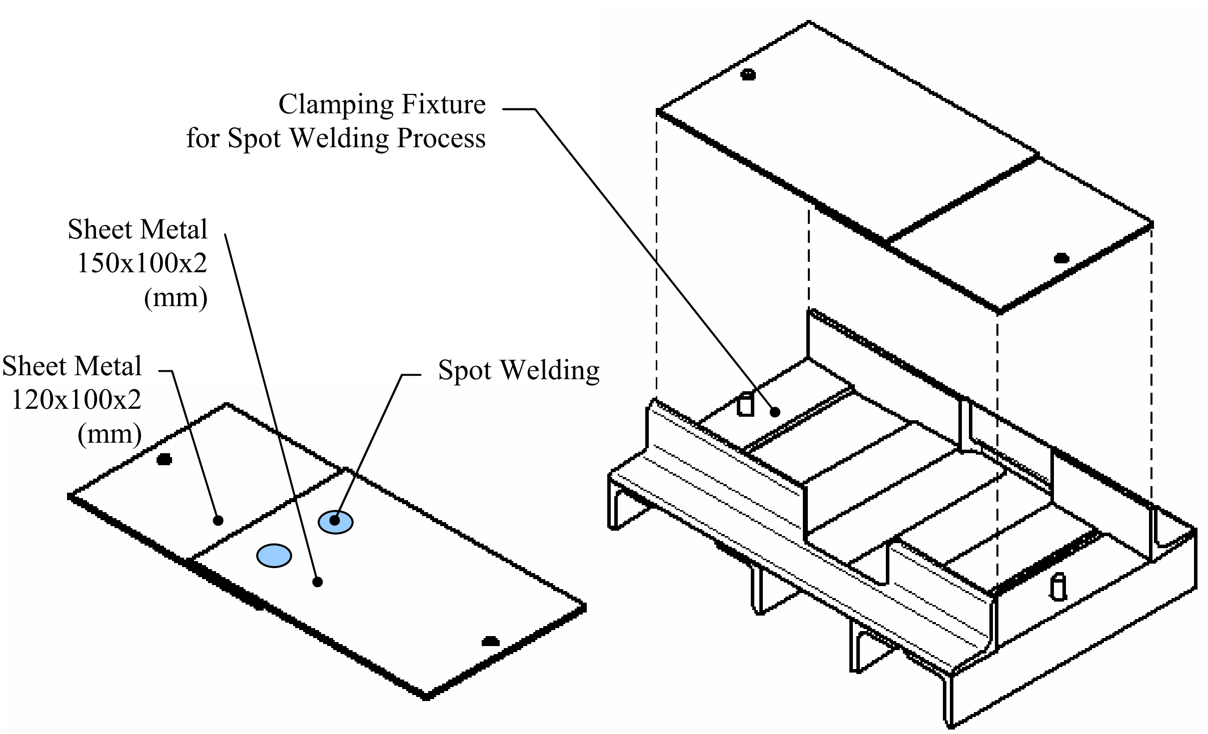


Figure 3. The analyzed sheet metal assembly

The admissible range of deviations caused by the manufacturing process of the steel plates used in this case is specified in the standard ISO 16160 and ISO 16162. Table 1 shows the dimensional and shape tolerances of continuously hot-rolled steel sheet products and cold-rolled steel sheet products respectively. These tolerances resemble the specification limits in combination with the permissible deviations defined in the technical drawing of the sheet parts. The main dimensions of the sheet plates (120 mm, 150 mm, 100 mm) are limited to a variation of ±0.3 mm and their thickness to a range of 0.2 mm symmetrically distributed relative to the nominal value of 2 mm. Besides a position tolerance of the centering drill-hole of ø0.5 mm the four edges of the sheet are toleranced relative to one long side with a perpendicularity of 0.2 mm and a parallelism of 0.4 mm.

Table 1. Dimensional and shape tolerances of continuously hot-rolled and cold-rolled steel sheet products

	Tolerances in pursuance of ISO 16160, [15]:	Tolerances in pursuance of ISO 16162, [16]:
Sheet metal thickness	2 mm	2 mm
Thickness tolerance	±0.17 mm	±0.13 mm
Flatness tolerance	[21; 32] mm/1200 mm	[10; 19] mm/1200 mm
	[1.75; 2.6] mm/100 mm	[0.83; 1.5] mm/100 mm

Based on the principles of "Design of Experiments" (DoE) up to 25 welded samples have been assembled in order to guarantee an appropriate significance of the performed tests.

4.2 The process to validate the approach

The validation of the developed concept to combine deviations due to tolerance zones with elastic deformations can be split up into three analysis steps using a common example for demonstration (figure 2).

Validation step 1: CAT Simulation using commercial applications

The first step of the validation approach is a computer-based simulation and analysis of the assembly process is performed considering the clamping fixture and the two parts with their tolerances. The models are calculated on two workbenches available and integrated in CATIA V5™: 3DCS™ and the recent module TAA™ (Tolerance Analysis of Deformable Assemblies). The workbench TAA™ allows an analysis of the deviations caused by manufacturing and joining processes based on a Finite Element Analysis [17] whereas 3DCS™ is one of the most popular CAT tools.

This software package allows an analysis of the rigid components based on the Monte Carlo Simulation technique. Regarding the tolerances defined in the specification ISO 16162 a model has to be built up considering the flatness tolerance of about 1 mm on the mating surfaces of the sheets. Measurement points highlighted with numbers 1 to 8 in figure 4 were defined within this model whereas points one to four belong to steelplate 150x100x2 and the remaining four points are situated on sheet metal 120x100x2. The tolerances are applied using the CATIA V5™ workbench FTA. In addition to the tolerances upon the part, positions and relations of the single parts are defined using "Moves" in the CAT tool in order to constrain the available degrees of freedom. The simulation is being performed with about 10000 calculation cycles. The postprocessing of the results allows an analysis of the nominal distances of the measurement points, mean values, standard deviation, process capability values as well as ranges.

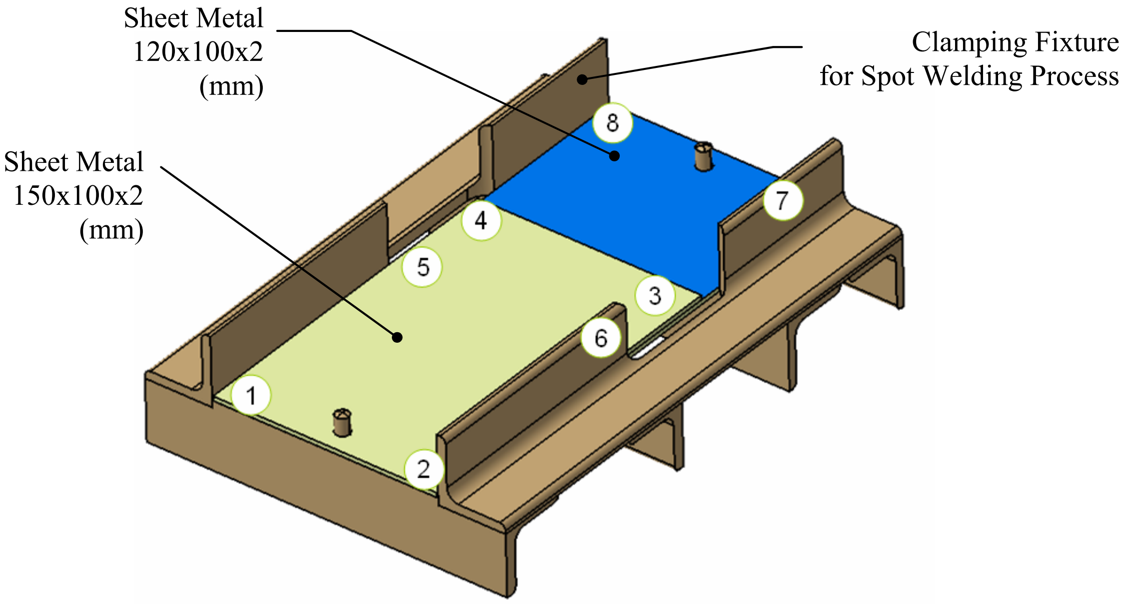


Figure 4. Rigid body CAT model with measurement points (1-8)

A further computer based analysis taking elastic deformations into account is performed using the workbench Tolerance Analysis of Deformable Assemblies of CATIA V5™. Starting with preprocessing of different models containing the two sheet metals joined by two spot welding points located within the overlap area the scenario with the best result is chosen for further consideration. One has to take notice of the complex process of applying deformations, positioning, first and second fastening and releases the structure hast to be performed within a scenario in TAA™. The results of the simulated scenarios permit an analysis of the resulting geometry depending on the displacements at the states mean plus or minus three times the resulting standard deviation.

Validation step 2: Integral Tolerance and Elasticity Analysis (ITEA)

Secondly the computer based simulation and examination of the described scenario based on the Integral Tolerance and Elasticity Analysis (ITEA) follows. Basis of this concept is a consistent description of tolerances and elastic deformations. So a uniform representation of both considered phenomena can be realized [13].

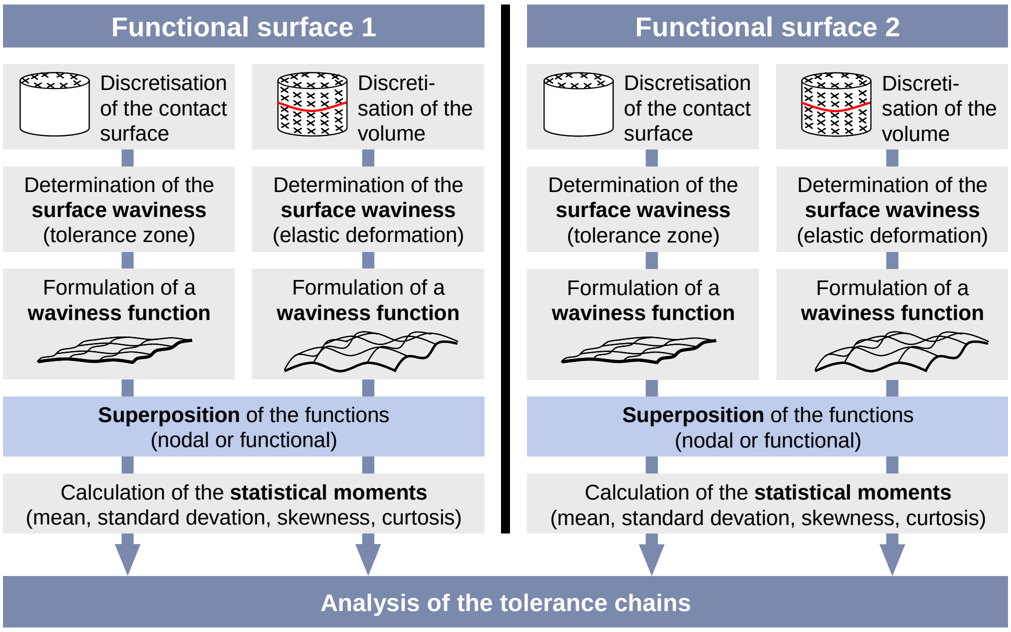


Figure 5. Linking concept

Manufacturing deviations as well as elastic deformations are detected pointwise and so those influences can be transferred into the desired representation by a suitable method of transformation (figure 5). When coupling elastic deformations and tolerance zones, each surface involved in a contact situation must be considered unlinked. Now it is imperative to make both phenomena manageable through respective discretisations (step A: discretisation of the contact surface/of the volume). In the detection of manufacturing deviations, the contact surface is coated by a dot matrix. Subsequently for individual points, the deviations from the respective nominal value in direction perpendicular to the surface need to be stored. Parallel to that a determination of linear-elastic deformations is effected by an FE analysis. For that purpose the component is fully meshed in which it is necessary to assure that nodal points also exist at points of the contact area, for which manufacturing deviations were stored before. This is done for reasons of the later necessary ability to superposition. The partial result consists of two models characterizing the surface in respect of both phenomena, however independent from each other (step B: determination of surface waviness). For better handling and generalization of the representation, these point models are transferred into trigonometric surface functions (step C: establishing the waviness function). Now these models are easily additively superposed by either reverting to the original point data (nodal) or by applying the functional representation (step D: superposition of functions). Thus the waviness of the contact surface is distinctly described now. On closer inspection, the resulting shape deviations can be seen as statistical frequency distribution of all contact surface points. This now allows to describe the occurring distribution by its so-called static moments (step E: calculation of statistic moments). These are in detail expected value (1st order statistic moment), standard deviation (statistic moment of order 2), skewness (statistic moment of order 3) and kurtosis (statistic moment of order 4). Of particular interest in this case are skewness and kurtosis as those are parameters describing a frequency distribution, which furthermore can be utilized for simulation purposes. Now any contact surface can be described integrally by these values. In the last step, parameters find access to a commercial tolerance analysis system that functions as simulation basis and core and in which each functional surface can be characterized separately.

Validation step 3: Experimental Mock-Up

The third step of this procedure covers the analysis of the performed experiments. Using the coordinate measuring technique the resulting deviations regarding flatness of the top of the assembly can be acquired as well as absolute deviations relative to the components initial coordinate system.

Moreover flatness measurements were performed on single parts as well as on the weldment in order to compare the influence of the manufacturing process on the assembly properties.

Targets of the absolute deviation measurement are the single parts and 25 welded components. The flatness is described by a value in mm and it is measured by a tactile sensor normal to the parts surface using a coordinate measurement machine. For comparison reasons a post-processing is performed building a regression plane. This element allows receiving flatness information for the measured surfaces. In order to receive detailed information about the shape of the analyzed part it is necessary execute a measurement based on single points distributed on the surface. An important prerequisite for this type of measurement is the definition of a workpiece coordinate system. Moreover an error correction concerning the radius of the sensing device has to be performed. A hand-operated measurement machine, Type MicroVal Brown&Sharp Mfg. Co. is used for a convenient collection of data. The signal providing the point coordinate data is detected by the sensing device RENISHAW TP-ES. About 55 to 70 uniformly distributed points have been measured per part to describe its surface.

5 THE RESULTS OF THE COMPARISON

The performed steps within the validation process allow an appropriate comparison of the real, measured deviations with the results of the common CAT tool analysis and simulation techniques for compliant components at this point. This comparison can carried out properly based on a preceding examination of the welding and measurement process revealing the origin of he measured deviations.

Check of the measurement data

The tests of the components based on the coordinate measurement technique permit conclusions about the flatness and tipping deviations of the single parts as well as for the assembled component resulting from the welding process. Comparing the mean flatness deviations one can see that the sheet metal placed first in the clamping fixture is deformed because of the process of welding. Regarding the mean deviations of the 25 tested assemblies evidences that the flatness deviations of the small sheet metal plate vary in range of 0.03 to 0.14 mm. These resulting deformations occur because of the type of constraining during the welding process (figure 6).

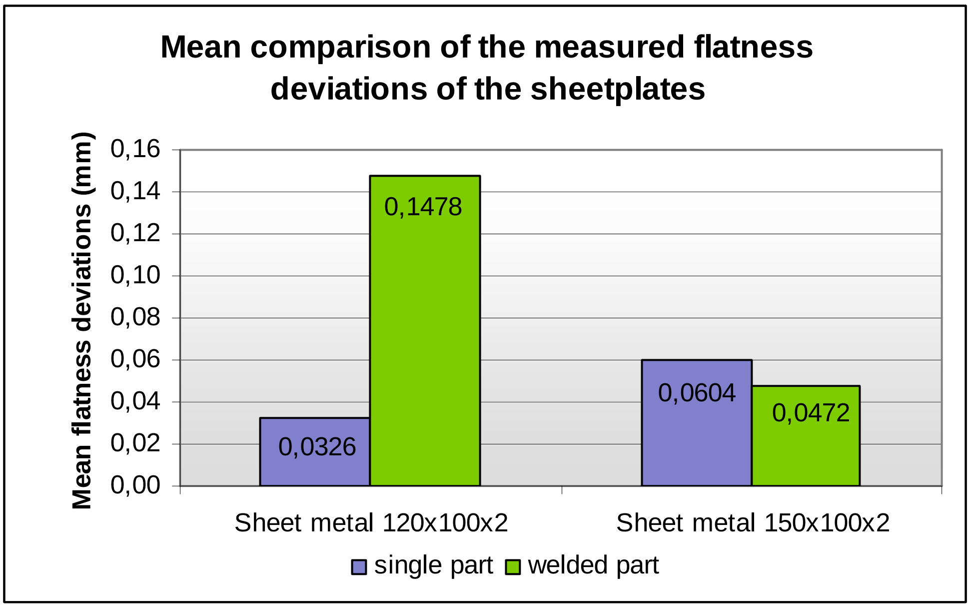


Figure 6. Mean comparison of the measured flatness deviations of the sheetplates within the deformed assembly

Comparison of simulation and measurement data

Regarding the results of measurement and simulation a comparison can be made based on pointwise part measurement and the flatness deviations. As comparison results the following statistical results like mean and standard deviation are used (see table 2). Due to the fact that input deviations defined by the tolerance defined in the specification exceed the real deviations there is a need to provide a value to achieve comparability (equation 1). The value was applied to all compared analysis results based on the results gained from CATIA V5™ workbench TAA.

$$v_{base} = 1 - \frac{R_{in}}{R_{out}} \qquad (1)$$

where

v_{base} = comparison value based on TAA

R_{in} = Inputrange

R_{out} = Outputrange

Table 2. Comparison: results of pointwise measurement

	Sheet metal plate 120x100x2		Sheet metal plate 150x100x2	
	z mm	Δz mm	z mm	Δz mm
Mean	2.019	0.019	2.018	0.018
Standard Deviation	0.014		0.028	
Minimum	1.992	-0.008	1.980	-0.020
Maximum	2.050	0.050	2.114	0.114

As an example of the results provided by the Monte Carlo simulation method the results of the simulation based on 3DCS are shown. The shown frequency graphs show a variation of the points mainly around the nominal mean value within the specification limit. The nominal value is the distance between the measurement point and the toleranced element and can be defined as 0 mm. For this reason the mean values of the distributions shown in figure 7 can be found close to the deviation of 0 mm.

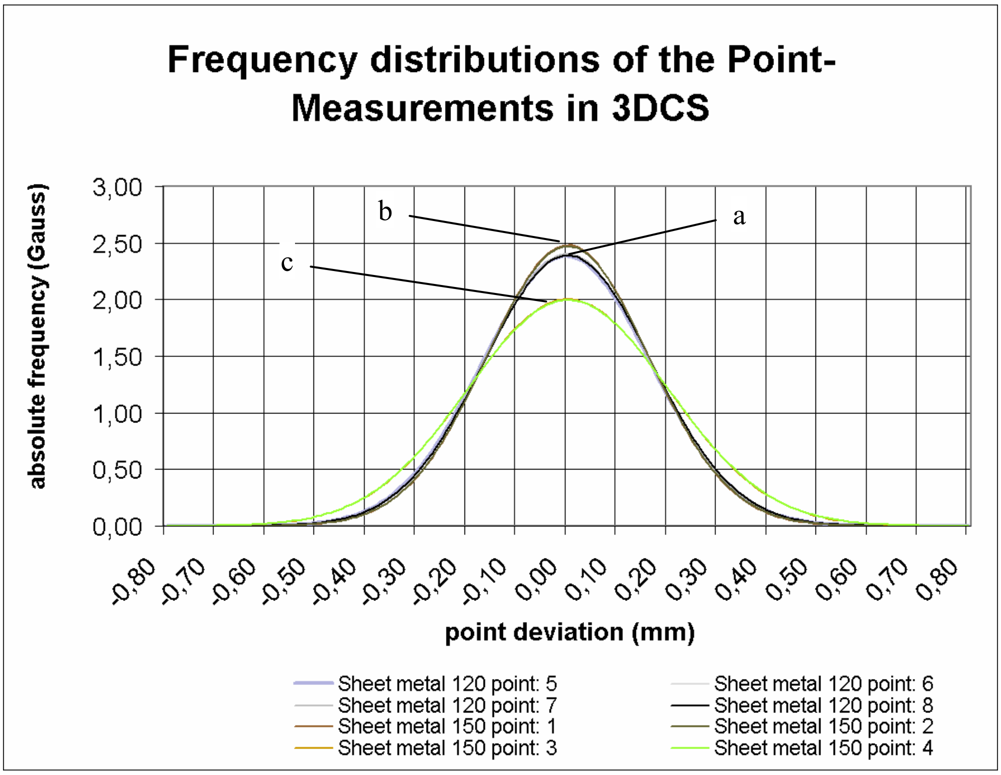
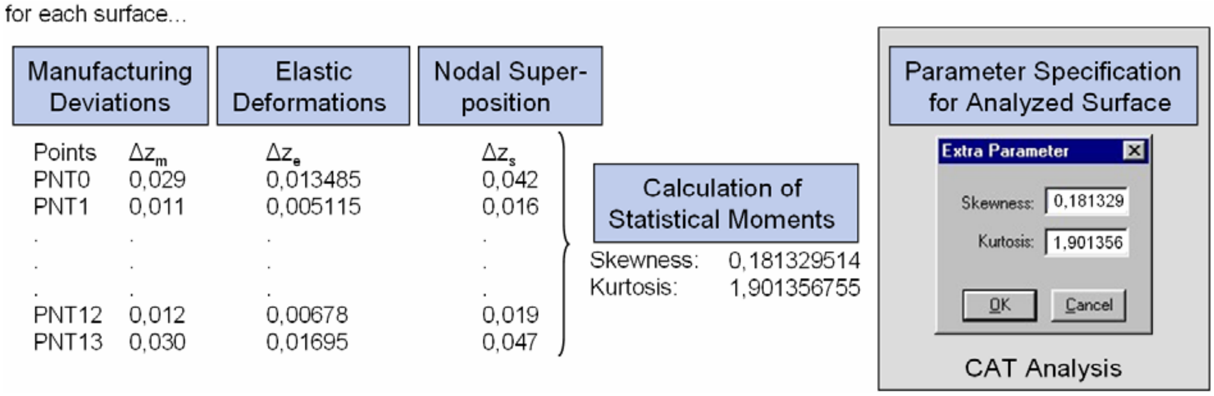


Figure 7. Frequency distributions of the point measurements in 3DCS

Due to the fact that the points 5 to 8 of sheet plate 120x100x2 are located at the rigid surface of the fixture and that the same flatness tolerance is applied the resulting distributions are quite identical (figure 7 curves a). The deviation of the large component within the assembly at the nodes 1 and 2 is influenced by the flatness tolerance as well as the propagation of deviations of the sheet plate with a

length of 120 mm (figure 7 curves b). Comparing this behaviour with the statistical results of there remaining points 3 and 4 an increase of variation can be discovered (figure 7 curves b).
The further evaluation process employing VisVSA™ for example shows similar results as those described in detail above. Those models are used to apply the concept of coupling tolerance analysis and elastic deformations to this assembly, whereas the full process has to be performed as described in section 4.2 "Validation Step 2". This process is shown in figure 8 for the chosen example.



Points	Δz_m	Δz_e	Δz_s
PNT0	0,029	0,013485	0,042
PNT1	0,011	0,005115	0,016
.	.	.	.
.	.	.	.
.	.	.	.
PNT12	0,012	0,00678	0,019
PNT13	0,030	0,01695	0,047

Skewness: 0,181329514
Kurtosis: 1,901356755

Skewness: 0,181329
Kurtosis: 1,901356

Figure 8. ITEA process for a surface of the chosen example

The measured manufacturing deviations Δz_m can be superposed with the elastic deformations Δz_e extracted from the Finite Element Calculation in order to get a set of data. This data can be used to calculate the statistical moments that are used for a specification of distribution-parameters in the CAT application. Based on the results of the tests and the assurance of comparability the following results can be put on record:

Table 3. Comparison of relative deviations

Methods	Relative deviations
Ratio 3DCS/TAA	7.1 %
Ratio Measurement/TAA	31.6 %
Ratio 3DCS/Measurement	36.1 %
Ratio Measurement/ITEA	15.3 %

It is important to mention that these results will depend on the use case and the way of comparison. So it is not recommended to transfer these ratios to other applications. The influence of taking elastic deformations into account must be evaluated for each task itself whereas the improvement of the CAT result can be both minor and major. On the other hand one of the most meaningful results from this validation process is the fact that a manipulation of distribution parameters can have enormous impact on the quality of the obtained results from a computer aided tolerance analysis. It was shown that an improvement of simulation preciseness can be achieved using the proposed approach of the ITEA.

6 CONCLUSION

A computer-based and experimental validation of an approach to combine tolerance zones with elastic deformations called ITEA was introduced in this paper. The need of taking elastic deformations into account was shown on an example and some use cases were presented. Moreover an outline of the state of the art was given describing the analysis of tolerance stack ups with software applications as well as research approaches. The concept of coupling tolerance analysis and elastic deformations was outlined shortly and described in detail within the presentation of the validation process that is based on three basic analyses. Furthermore the collection of data used for comparison of the methods was presented. Finally a quantification of the benefit within the use case of a manufacturing process was introduced and the improvement of of the standard CAT technique using rigid bodies was highlighted. The important aspect of being able to improve the accuracy of CAT simulations by superposing deviations and analyzing them statistically was outlined. This benefit may even be of major importance regarding precise and highly stressed components.

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