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VIRTUAL DIMENSIONAL PRODUCT VALIDATION BY INTEGRATION OF SIMULATIONS

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ABSTRACT
The process of virtual validation of product function has an important role in product development. It enables the product developer to design products taking different aspects like Design to Quality into account. Reliable results of simulations can only be obtained if appropriate assumptions for the model exist. Therefore the aim of this contribution is to suggest an approach to estimate input parameters of computer aided tolerancing simulations (CAT). For this purpose stochastic manufacturing process analysis is performed. Based on an analysis of the dimensional modelling process and an overview of tolerance analysis techniques, a concept for estimation of simulation assumptions for CAT is systematically derived. The identification of pivotal model parameters in tolerance analysis and the integration of results of a manufacturing process simulation are outlined. Based on simulations of an example application the manufacturing simulation parameters and the resulting process variations for use in tolerance analysis are described. Finally the impact of these parameters on dimensional quality measures is discussed. To conclude, an outlook on further integration of processes is given.

Keywords: Dimensional management, computer aided tolerancing, stamping simulation, D-to-Quality

1 PROBLEM STATEMENT AND OBJECTIVES
Modern methodologies and tools enable the product developer to design products taking different aspects like Design to Reliability or Design to Quality into account. The process of virtual validation is one of the pivotal tasks during product development e.g. in automotive industry. Due to the demand for frontloading an intensive application of simulations in product development establishes and the need for precise analysis techniques increases. A high accuracy of simulation results is demanded and therefore much effort for the optimization of analysis and optimization methods is spent in research. Concerning quality measures, which assure product function, this can be observed in research on tolerancing models and methods ([1], [2], [3], [4], [5]). The improvement of these techniques also causes an increase of their sensitivity and the need for identification and determination of the pivotal simulation parameters arises. In contrast to this it can be observed that a plenty of simulation parameters have to be estimated in CAT analysis and a considerable amount of assumptions is incorrect. Thus a concept for integrating manufacturing simulations in the process of dimensional management is proposed in this paper in order to determine and estimate analysis parameters. This contributes to a simulation driven product development leading to robust products based on more reliable results and statistical analysis.
The analysis of tolerances using tolerancing models, calculation methods and simulation applications is embossed by modelling simplifications and assumptions [6]. Therefore the following research problems arise:

1. What kind of parameters are the crucial ones for computer aided tolerancing (CAT)-simulations? (section 2.1)
2. Which tools/methodologies exist and can be employed for the reliable determination (or improved estimation) of simulation boundary conditions and assumptions? (section 2.2)

Main objective of the research presented here is the improvement of tolerance analysis accuracy using simulation results from previous process steps. Therefore a concept of a process model is set up and discussed in order to achieve improvements in virtual dimensional product validation (section 3). Regarding the first steps of research results three aspects are focused here:

- An analysis of tolerance analysis techniques provides information on pivotal parameters.
- An analysis of manufacturing simulation technologies for stamped sheet metal parts allows the

determination of crucial process (simulation) parameters and resulting dimensional, form- and location-errors. So a prediction of possible and manufacturing deviations can be obtained.

- A methodology for integration of the statistical deviation data into CAT has to be derived. The impact of taking estimated manufacturing distributions into account has to be verified. This is implemented setting up and comparing a) a reference model and b) models including manufacturing simulation results.

A case study is performed (section 4) in order to illustrate the modelling process and the benefit of the approach suggested in this paper. Therefore the aim of this contribution is to suggest an approach to estimate input parameters of CAT using stochastic manufacturing process simulation.

2 WORK METHODOLOGY

In this section the dimensional management process and its theoretic framework is analyzed. The results of a literature review concerning model parameters in tolerance analysis are presented. They allow a specification of the parameters to be derived from manufacturing simulations. Furthermore a manufacturing process is chosen for analysis of the state of the art regarding simulation of deviations. These considerations serve as a basis of deriving a concept of integration.

2.1 Pivotal Tolerance Analysis Parameters

Dimensional Management has two major objectives in the product development process: tolerance synthesis and tolerance analysis. They can only be performed if a consistent model of tolerance specification exists (such as parametric tolerance definitions). It allows specifying the functional behaviour of a system regarding deviations by setting up a tolerance model. So a mathematical formulation of the tolerancing problem can be derived [7]. The relationship of input variables and system responses in a mechanical assembly is expressed by

$$X = f(y_1, y_2 ..., y_n) \qquad (1)$$

where y_i ($i \in \{1, \ldots, n\}$) are input parameters with known distributions/lower order statistical moments and X represents the assembly response. Based on this (linear or nonlinear) functional behaviour various calculation methods exist to determine the deterministic and stochastic behaviour of the assembly deviations. A selection of these methods is shown in the following overview:

- Worst Case Method ([8], [9]),
- Root Sum Square ([7], [8], [9]),
- Estimated Mean Shift Model ([10]),
- Croft's Method ([7]),
- Hasofer-Lind-Index ([7]),
- Taguchi´s Method ([7]),
- Method of System Moments ([11]),
- Second-Order Tolerance Analysis ([11]),
- High Low Median Analysis ([12]),
- Monte Carlo Simulation ([7]),
- McCATS ([13]).

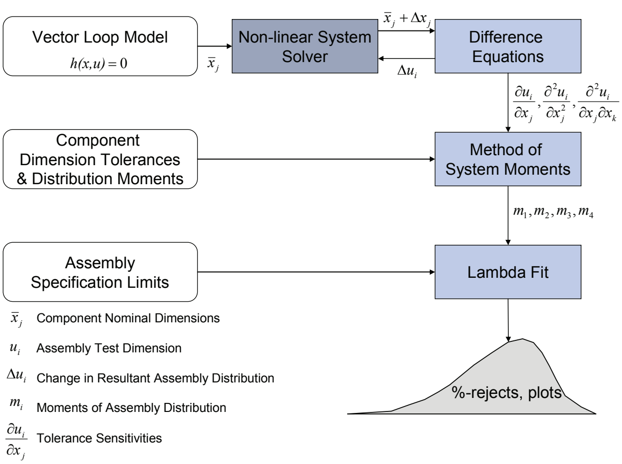

Figure 1. The SOTA method [11]

For purposes of reviewing the performed analysis the model of Glancy [11] is chosen for the outline: All of the methods shown above and in Figure 1 are based on a tolerancing model. In [11] a Vector Loop Model is employed for example. This leads to a mathematical representation of the assembly and its response.
The methods for estimating the assembly result depend on a definition of component dimension tolerances and the distribution for a certain dimension related to the manufacturing process (the GTOL-C_p and -C_{pk}). The assembly specification limits compared to the response distribution finally serve as indicator of product quality. Process capability indices like process precision C_p, process accuracy C_a or process capability C_{pk} can be easily calculated for purposes of analysis [14]:

$$
\begin{aligned}
C_p &= \frac{USL - LSL}{6\sigma} \\
C_{pk} &= \min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} \\
C_a &= 1 - k = 1 - \frac{|\mu - m|}{0{,}5(USL - LSL)}
\end{aligned}
\tag{2}
$$

where USL is the upper specification limit, LSL is the lower specification limit, σ is the process standard deviation, μ is the process mean, m is the midpoint between USL and LSL.
The assumptions and model parameters shown in Figure 1 as well as those in the approaches mentioned above allow the identification of a set of variables available for affecting the tolerance analysis result like C_p. Based on the mathematical formulation of the method or its processing model (SOTA, MCS) the following parameters can be derived as possible ways to exert influence on the result of an analysis:

A: Tolerance Specification

- mean shifts,
- statistical moments (up to fourth order),
- T/t-adjustment (equivalent to GTOL-C_p-adjustment).

B: Tolerance Model

- additional vectors,
- definition of model elements (dimensional change, normal, shifts).

This list represents a number of model parameters that are liable to assumptions in the tolerance modelling process. They are varied in a sensitivity analysis discussed in section 4 in order to determine the crucial parameters for CAT-simulation.

2.2 Tools for the Prediction of Manufacturing Deviations

The process of sheet metal forming is selected as manufacturing process in this work because of the following reasons:

- availability of powerful simulation tools employing accurate material models and taking multistage process steps into account (gravity, holding, stamping, springback) [15], [16],
- highly geometry-dependent process and so,
- non- or hardly-transferable geometric deviations like springback [17] and thickness distributions [16],
- range of simulated deviations is in similar regions as tolerances of sheet metal parts [16],
- wide use in automotive industry for parts in car body assemblies [17].

Stamping is a process which is liable for a multitude of influences. The use of simulation software allows an analysis of the metal forming process. In order to obtain reliable results it is required that FE-based software allows the regard of pivotal parameters of the process. These parameters can be split up in sections material, workpiece and process parameters. The influence on the accuracy of the result is shown in the Ishikawa-diagram in Figure 2.
In order to determine tools for the prediction of manufacturing simulations a comparison of available software applications was performed based on the following criteria:

- time integration methods (implicit/explicit/single step),
- springback calculation,
- calculation accuracy,
- springback compensation,
- CAD-interfaces,
- forming limit diagrams and rupture risk reporting capabilities,

- fast feasibility analysis,
- tool design,
- process design,
- reliability analysis/six sigma modules,
- availability.

Finally the software PamStamp 2G™ was chosen because of high accuracy of the system responses accompanied by huge sets of process macros and license accessibility. The software allows the variation of process parameters according to Figure 2 and [16] for example. Using methods of reliability analysis as described in [16], [18] a statistic response can be obtained. This enables the estimation of geometric deviations for tolerance analysis.

In this section pivotal parameters of tolerance analysis and sheet metal forming processes were described in order to select adequate methods and tools for simulation. It was shown that there are adequate tools for the determination or improved estimation of simulation boundary conditions and assumptions assisting the virtual product development process.

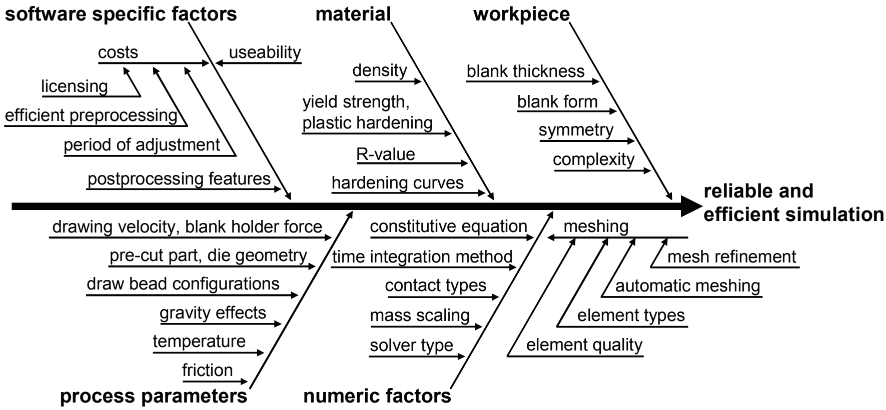

Figure 2. Ishikawa-diagram for sheet metal forming simulation

3 CONCEPT FOR THE INTEGRATION OF MANUFACTURING SIMULATIONS INTO TOLERANCE ANALYSIS

The knowledge of pivotal parameters of tolerance analysis and stamping simulation responses allows the proposal of a concept for the integration of manufacturing simulations into tolerance analysis. It has to be shown in this contribution that the efforts made in performing a series of simulations contribute significantly to the improvement of tolerance analysis process. This concept is based on

- methods of design of experiments (DoE),
- methods of robust design,
- manufacturing simulations,
- simulations of compliant parts and
- tolerance analysis methods/tools.

As shown in Figure 3 the process starts with a probabilistic simulation of stamped parts. Therefore the set of probabilistic variables like material properties or process parameters like blank holder force have to be determined. This information can be gathered performing standard material tests and from measurement data of similar manufacturing processes. The variation of the parameters in stamping simulation leads to *n* deterministic, deviated part geometry models. The resulting meshes are analyzed using methods of coordinate metrology to determine deviations of geometric features from given specifications. So a set of deterministic and/or probabilistic indicators is derived regarding manufacturing simulation. Using one ore more meshes embodying deviated part geometry an FE-based compliance simulation can be performed whereas the scatter of part deviations in the region of joints or fixtures is now available from stamping simulation. A lot of research was spent in the past concerning this issue [1], [4], [5], [19] and software packages (like FEA option for Siemens Teamcenter Visualization VSA™ or Dimensional Control Systems FEA Compliant Modeller™) exist for this purpose. This simulation results in a deviated assembly geometry. Depending on the loadcases during product use other studies based on deviated part and assembly geometry are performed to determine the impact of geometric errors (similar to [20]).

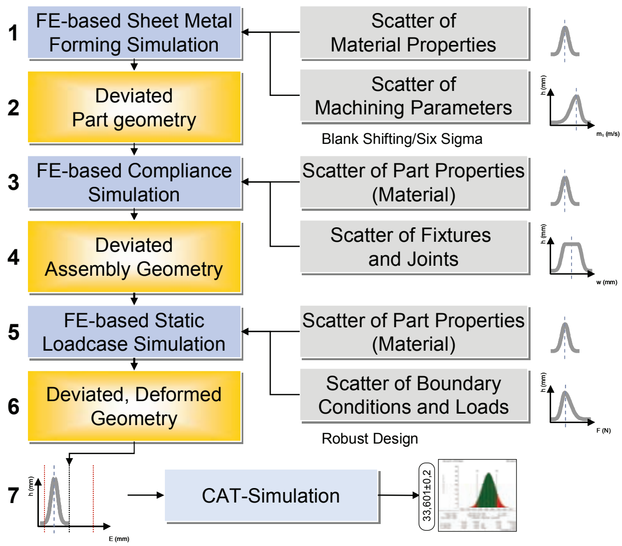

Figure 3. Concept for the integration of manufacturing simulations into tolerance analysis

The methods of coordinate metrology for determination of geometric deviations are employed at each stage to determine geometric deviations (caused by manufacturing, assembling and loading during product use). The sets of deterministic and/or probabilistic indicators derived are used as input for tolerance analysis (as shown in section 2.1). So this concept proposes the integrated simulation of multistage processes including product use in order to obtain more reliable and accurate computer aided tolerance simulation results. This concept does not resemble a generic math model [2] but a statistical/probabilistic model for variation propagation analysis. One of the basic concepts of this approach is – as outlined in [7] – the simulation of process capabilities rather than tolerances: *"[...] it is the statistics of the process which should be used in the tolerance analysis."* This paper focuses on steps 1, 2 and 7 only with the purpose of highlighting the contribution of stamping process to final assembly quality.

4 CASE STUDY RESULTS

The case study is based on a simple assembly of two sheet metal parts. The parts are rotationally symmetric and feature a cup-shaped section. The parts are manufactured in a one-stage sheet metal forming process and assembled – for a first examination – without clamping and joining operations (see Figure 4). It resembles for example a subassembly of an automotive shell construction.

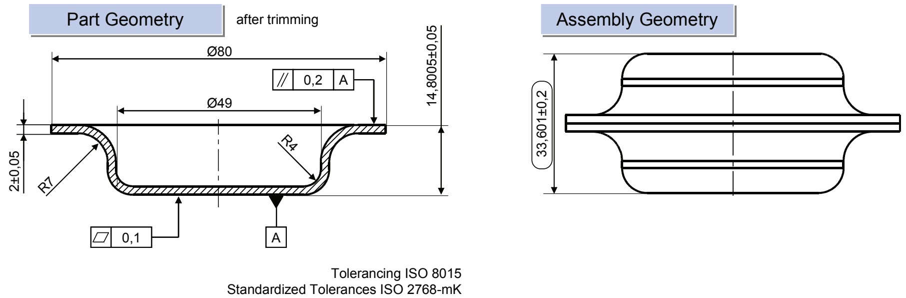

Figure 4. Case study geometry (simplified)

The research presented in this case study focuses on three steps of the proposed concept: FE-based Sheet Metal Forming Simulation (1), analysis of Deformed Part Geometry (2) and CAT-Simulation (see Figure 3). The others are omitted for first evaluation. To identify the pivotal parameters of stamping simulation for the assembly the steps 4.1 Sheet Metal Forming of the Cup-Shaped Section, 4.2 Geometric Evaluation of Simulation Data, 4.3 Tolerance Analysis Results are performed (Figure 5) and outlined in the following sections.

4.1 Sheet Metal Forming of the Cup-Shaped Section

The geometric deviations resulting from manufacturing processes are derived for the cup-shaped part from simulations using PamStamp 2G™ (ESI Group). First of all an initial model of the stamping process is set up. Based on this reference model a variation of process parameters is conducted. The levels of variation are taken from studies [21] and literature [16]. The probabilistic variables used in this study are:

- yield strength k_f, plastic hardening modulus $E_{\tan}$, and Lankford coefficients $R_{00}-R_{45}-R_{90}$,
- coefficient of friction between blank, blank holder, die and punch μ_f,
- position u of the sheet metal along the x- and y-axis (depending on the rolling direction),
- blank thickness s_t.

These parameters are varied using a factorial experimental design of these independent coefficients due to DoE [22]. Only one factor at a time is changed in order to obtain a reliable sensitivity analysis. The yield strength scatter is chosen equidistantly about the mean of $\bar{k}_f = 600.22\frac{N}{mm^2}$ with a standard deviation of the sample of $s_{k_f} = 12.64\frac{N}{mm^2}$ at approximately the $\pm 1s_{mat}$ levels shown in Table 1.

Table 1. Levels of the Experimental Design Study for Material Properties [16]

Level	k_f	$E_{\tan}$	R_{00}	R_{45}	R_{90}
$+1s_{mat}$	611	2689	0.765	0.793	1.028
$\bar{x}_{mat}$	600	2760	0.760	0.807	0.993
$-1s_{mat}$	595	2697	0.817	0.800	1.076

The coefficient of friction between blank, blank holder, die and punch is varied at levels of $\mu_f = 0.1 \pm 0.01$. The position of the sheet metal along the x- and y-axis is varied at $u = 0.0 + 0.3\,mm$ (mean gap in positioning device of process) from the initial position at level + in parallel to rolling direction and normal to rolling direction in level -. The blank thickness s_t of a 2 mm sheet metal cold rolled steel is varied on four levels about the mean of $\bar{s}_t = 2.019\,mm$:

$$+2s_{\bar{s}_t} : s_t = 2.049\,mm, \quad -2s_{\bar{s}_t} : s_t = 1.989\,mm \quad +6s_{\bar{s}_t} : s_t = 2.109\,mm, \quad -6s_{\bar{s}_t} : s_t = 1.929\,mm \tag{3}$$

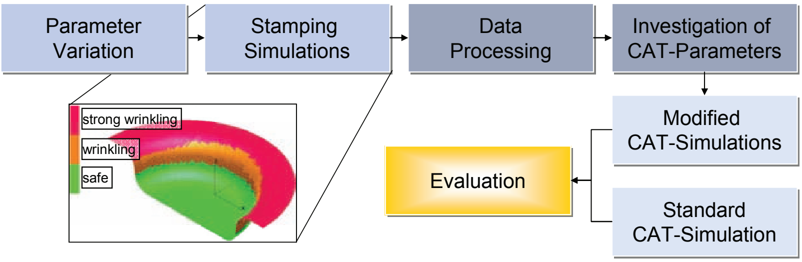

Figure 5. Evaluation process for the integration of manufacturing simulations in CAT

An evaluation using the capabilities of the sheet metal forming application shows the geometric deviations resulting from parameter variation. The measurement is performed node by node from trimmed state to springback state of the simulation. Non-Euclidean distances between all nodes (i.e. no feature selection) are evaluated. A Pareto-Analysis of the contributors to the final deviation reveals the following sequence of parameters ordered by influence on the resulting geometric deviations for this case study:

1. blank position,
2. material parameters,
3. friction,
4. blank thickness.

Moreover it can be derived – bearing in mind that parameters are varied on different levels of standard deviation – that blank position and material parameters cover about 90% of the ratio.

4.2 Geometric Evaluation of Simulation Data

The use of the stamping results for tolerance analysis affords an evaluation of the geometry in a way that is compatible with model parameters (tolerance specification, tolerance model; section 2.1) of the CAT-simulation. The processing of the FE-result data has to be performed for each geometric feature with assigned tolerances of size, location, form and/or orientation. Regarding the cup-shaped parts in the assembly size tolerances of blank thickness, total height and diameter 80 mm can influence the dimension of interest. Moreover the flatness tolerance and the parallelism of the flange depending on datum A take effect on the test dimension of 33.601 ±0,2 mm. To determine the deterministic and statistic parameters of the stamping simulations an analysis employing regression planes is performed (see Figure 6).

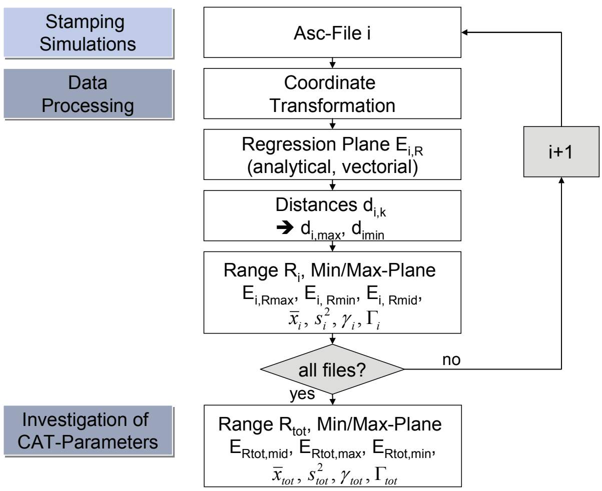

Figure 6. Data processing of point cloud data for plane features

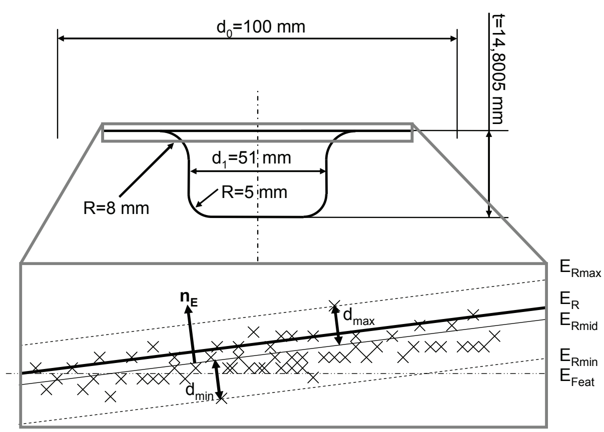

Figure 7. Data processing for midplane model

Starting from n Asc-files resulting from factorial design of stamping simulation for each file a coordinate transformation from Cartesian to polar coordinates is accomplished. The files contain

information on midplane-deviations and thickness change (shell-elements). Based on a selection of points (the flange for example) a regression plane $E_{i,R}$ can be derived in analytical form. Setting up a vectorial representation of $E_{i,R}$ by calculation of a model point and two vectors allows the identification of the distances $d_{i,k}$ of each point in the point cloud (see Figure 7).
Storing the minimum and maximum of $d_{i,k}$ a set of parameters can be calculated:

- Min- and Max-Planes $E_{i,Rmin}$ and $E_{i,Rmax}$ based on $d_{i,max}$ and $d_{i,min}$,
- Midplane $E_{i,Mid}$ (unequal $E_{i,R}$),
- Range R_i,
- Statistical moments up to fourth order: mean $\bar{x}_i$, standard deviation s_i, skewness γ, kurtosis Γ.

This process has to be performed for each of the n stamping simulation result files leading to a set of statistical parameters ready for use in tolerance analysis (C_p-modifications, mean shifts, …). The analysis of the stamping data in the case study showed the following results:

Form deviation of the cup-shaped part floor: flatness

- plane normal (-0.0012; -0.0061; -1.0000),
- plane point (x_p, y_p+0, z_p),
- Cp-adjustment: $T=T_p+0.1914$ mm,
- shift of plane 0,0318 mm,
- mean shift 0.0318 mm,
- skewness 0.6942,
- kurtosis -0.4930.

Location deviation of the flange: parallelism

- plane normal (0.0014; 1.0; 0.0040),
- plane point (x_p, y_p-0.1662, z_p),
- Cp-adjustment: $T=T_p-0.0954$ mm,
- shift of plane 0.0022 mm,
- mean shift 0.002 mm,
- skewness -0.0560,
- kurtosis -0.3965.

Size variation of distance t 14,8005±0.1 mm:

- Cp-adjustment: $T=T_s+0.0235$ mm,
- mean shift 0.0022 mm,
- skewness 3.0522,
- kurtosis 9.8701.

These results apply due to symmetry of the assembly to both top and bottom part (cf. Figure 4). For features other than planes different strategies of data processing like minimum circumscribed circles or similar have to be performed.

4.3 Tolerance Analysis Results

Modelling and Simulation Results

According to Figure 5 the investigation of CAT-parameters is followed by modelling of the tolerancing problem. Based on the basic modelling of the tolerancing problem the CAT-simulations of the reference model and the modified models are performed.
The process of modelling depends on the software package used for tolerance analysis. In this case study Siemens PLM Teamcenter Visualization Mockup™ module VisVSA is used. The setup of the model starts converting and importing geometry of parts and assembly. The process document is supplemented by deriving the features for tolerance analysis by selection of the related part geometry. The model features conduce to the definition of datum references and specification of tolerance kind and value. In addition to these basic parameters, zone shifts and mean shifts can be applied to the features and distributions (Normal, Uniform, Extreme, Pearson) for use in simulations can be specified. The model set up is completed by definition of assembly moves and measurements. The measurements in this virtual mock-up represent the response of the system as outlined in section 2.1 and equation (1). A formal validation of the study has to be performed before running Monte Carlo Simulations and HLM-simulations with a set of simulation preferences defined for analysis: number of Monte Carlo Simulations, the run of extreme simulations, mean shift calculations, tolerance sigma range, evaluation of interference builds and others. Finally the results can be exported or visualized and evaluated using statistical information on the measurements defined like mean, standard deviation, range and process capability indices (see equation (2)).
In this case study an initial model was set up using nominal CAD-geometry and tolerance specifications originating from a previously performed tolerance synthesis based on analytical RSS-method [7] resulting in an improved set of tolerances. The model was used as a basis of the subsequent simulations in order to ensure comparability. Analytical tolerance synthesis and optimization are an important stage concerning this evaluation because the initial model serves as reference for the

subsequent ones (unless no physical experiments are performed to prove the proposed methodology). The initial model is named A1B0, whereas the last index labels the degree of integration of manufacturing simulation results ranging from 0 to 4. The model A1B1 is improved compared to model A1B0 by an adjustment of the plane feature orientations and the plane feature origins according to the regression plane in Figure 7. The adjustment results in a rotation and translation of the simulated deviation area (cf. Figure 8). In model A1B2 the range of the initial tolerance range is changed in a way that the tolerance range now corresponds to the range determined from stochastic stamping simulation. A further adjustment has to be performed in model A1B3 because the ranges of model A1B2 do not already coincide regarding upper and lower limits. This can be achieved within the software tool using zone shift followed by a mean shift ensuring that the process mean from stamping simulation coincides with simulation mean again. Finally the type of distribution can be adjusted to the statistical behaviour resulting from stamping simulation data processing in model A1B4. This model includes all statistical information gained from stamping simulation data processing. Figure 8 shows an adjustment for the plane feature representing the flange of the case study parts.

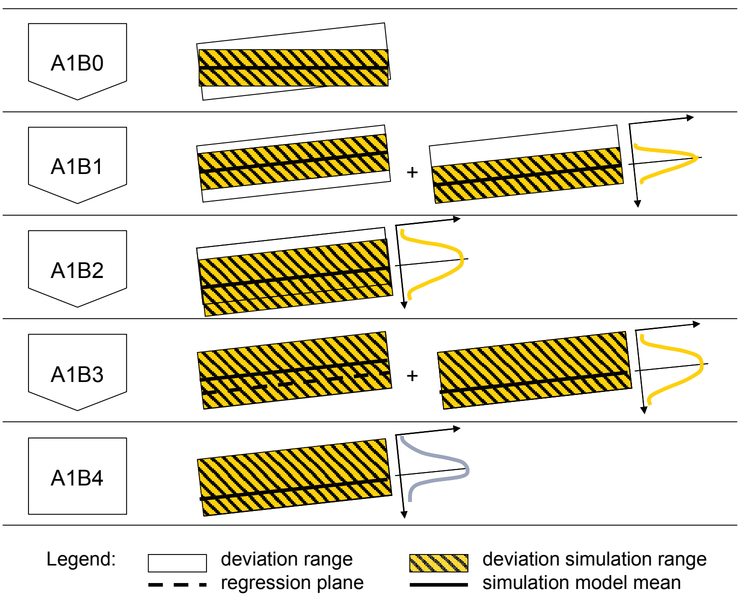

Figure 8. Plane feature adjustment for integration of stamping simulation results into CAT

Table 2. Simulation results of quality measure 33.601 mm

Model	Mean in mm	Standard deviation in mm	C_p-value	C_{pk}-value	Range in mm
A1B0	33.58416153	0.04694968	1.423701196	1.30383526	0.47333621
A1B1	33.23238716	0.04928952	1.355563829	-1.13282817	0.46719113
A1B2	33.11684553	0.08157969	0.827544342	-1.15069267	0.73120946
A1B3	33.12126078	0.08157991	0.825308925	-1.13422486	0.73120953
A1B4	33.14840793	0.07971061	0.864127709	-0.95154856	0.70275963
δ(A1B0-A1B4)	0.4357536	-0.03276093	0.559573487	2.25538382	-0.22942342

In order to perform a sensitivity analysis the models A1B0 to A1B4 are calculated individually and evaluated observing the system response as shown in Figure 4. About 1.000.000 Monte Carlo simulation runs are performed for each model using the CAT simulation software. Mean, standard deviation, C_p, C_{pk} and range are compared in this case study. The results of the evaluation are shown in Table 2. The last row shows the difference of model A1B0 compared to A1B4.

Discussion of the Results Obtained from Integrated Simulation

The results from the integration show significant changes on some of the stages. An adjustment of process features by changing the plane normal and the origin of the plane causes a change of the mean and (due to its definition (2)) a shift of the C_{pk}-value. This can be traced back mainly to the plane origin shift in this example because of the deviation of the nominal compared to the stamping geometry. An increase of standard deviation can be observed regarding models A1B2, A1B3 and A1B4 compared to A1B0 und A1B1. This can be put down to the significant modification of the admissible deviation ranges in the simulation model. Due to the fact that specification limits of the measurement are identical for all models, the C_p-value is influenced by standard deviation only (cf. equation (2)). The change in standard deviation causes a significant decrease of the C_p-values comparing all models. It is worth mentioning that only models A1B0 and A1B1 meet the requirement of a C_p-value > 1.33. Analyzing the performed sensitivity study, it can be derived that a dramatic shift – caused by the feature adjustment according to the calculated regression planes – in the C_{pk}-value can be observed. Regarding the results of the reference model A1B0 compared to the model taking mean shifts and normal modification as well as skewness and kurtosis into account, the following results can be derived:

- The sensitivity analysis shows that an initial mean value of the test dimension 33.58 mm changes about a value of 0.44 mm.
- Though standard deviation is small, 0.05 mm, an increase of 70 % is determined.
- This change results in a C_p loss of about 0.56 (1.42-0.86). Accounting for the efforts made in manufacturing to achieve a 0.1-improvement, this loss is enormous.
- Due to the adaption of the tolerance range at model A1B2 a significant change in ranges can be observed in this assembly problem. The range increases about 49% compared to the initial model.
- Moreover a dramatic C_{pk}-shift is observed: whereas the initial C_{pk} of 1.30 is very close to the initial C_p-value the C_{pk} of model A1B4 shifts to -0.95 which is a significant change in the results.

It is worth mentioning that the comparison of A1B0 and A1B4 corresponds to the comparison of modelling without taking manufacturing simulations into account and the proposed integrated approach. Finally it can be concluded that according to the significant changes in analysis results process simulation results should be integrated (based on the proposed concept for example). Taking statistical simulation data from previous process steps into account can significantly change CAT-simulation results and thus conclusions on product function (in this case for example operation range of a sealing between car body and hatch). This leads to more reliable results in CAT-simulation and allows a development of premium-quality, robust products. For sure, this improvement is based on reliable (but determined by quality control) material property information and stamping simulation.

5 CONCLUSION AND FURTHER WORK

In this paper pivotal simulation parameters of tolerance analysis and manufacturing simulations are determined based on literature review and simulation based sensitivity analyses. It was derived that a set of parameters regarding tolerance specification and tolerance models is available for CAT-adjustment. Parameters for sheet metal forming simulation are derived from literature in order to be able to perform probabilistic simulations. Finally a concept for integrating manufacturing simulations in the process of dimensional management is systematically derived and introduced in this paper in order to determine and estimate analysis parameters. A case study of an assembly of cup-shaped parts is used for the accomplishment of a) probabilistic stamping simulations, b) data processing for obtaining results on geometric deviations and c) tolerance analysis. Regarding data processing results it can be concluded that it is required to acquire various statistical information on size variations (skewness kurtosis) and form/location variations (mean shifts, normal). The result of the Monte-Carlo based CAT-Simulations reveals that it is important to take simulation results of manufacturing processes into account. *Rather then simulating tolerances a simulation of process capabilities has to be performed as proposed in [7]*. This leads to a significant improvement of tolerance analysis accuracy based on accurate manufacturing simulations. It can be derived that all elements of the presented set are pivotal parameters of tolerance analysis: range-based T/t adjustments (equivalent to GTOL-C_p adjustment) significantly affect standard deviation and C_p of the test dimension. The

adjustment of model elements (vector of plane normal, shift of plane) and the inclusion of statistic moments (skewness, kurtosis, mean shifts) significantly influence mean and C_{pk}.
A further direction in research is to verify accuracy of these results performing an experimental validation using cross-shaped probes. A similar evaluation process compared to [21] is planned to substantiate the effectiveness of the concept compared to the conventional tolerance analysis assumptions. Furthermore the extension of the concept for assembling and joining processes for compliant parts must be taken into account (see Figure 3). This will be complemented by the analysis on the elastic behaviour of parts/assemblies in product use employing robust design tools according to [23]. Even other processes like injection moulding will be of interest in further research.

6 ACKNOWLEDGMENTS

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