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Tolerance Optimization Considerations Applied to the Sheet Metal Compliant Assembly

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ABSTRACT

Sheet metal parts are widespread used in the assembly of product such as automotive and airframes bodies. This paper presents how Dimensional Engineering (DE) process and the simulation-based tolerance analysis used in the development process of the assembly tolerance analysis. Focusing on the sheet metal component, which should be treated as non-rigid part, compliant assembly analyzing is adopted in the simulation process. Deviations of the components due to the tolerance between pin locator and hole and the locator layout scheme are defined as the key point characteristics (KPCs) during the optimization process. Inspection data incorporated close-loop optimizing approaches is applied to the final deviation estimation in simulation. Dimensional engineering software solution, 3DCS, is used as the analyzing tool in the case study

Keywords: sheet metal assembly, compliant assembly, tolerance analysis, 3DCs.

1. INTRODUCTION

The dimensional integrity of an automotive body has tremendous impact on the quality of the final vehicle. Optimizing for dimensional integrity improves the robustness of design and processes. The aim of it is maximizing part tolerances with controlling the dimensional assembly requirements of the final assembly.

A typical body-in-white (BIW) which is the automotive body without closure panels such as the doors, hood, and deck lid, and without paint applied, consists of approximately 150–250 stamped sheet metal parts. Sheet metal parts, with a small ratio of thickness to width or length, are widely used in automotive and aerospace industries. Those parts are assembled into the BIW throughout the whole assembly process. Pin-hole type joint and redundantly restrained positioning are widely adopted in this type of assembly. Sheet metal parts are substantially flexible and prone to large errors due to elastic deformations during assembly processing. The final assembly variation is caused by errors in locators and flexibility of individual components. Fixture force, spring back, welding (riveting) distortion play major roles in the procedure of errors transform.

When dealing with the assembly of sheet metal parts, engineers face many obstacles. They often find themselves:

- Spending a lot of time reworking or repairing parts that:
  - Fail inspection, but may fit and function properly when assembled.
  - Pass inspection, but do not fit with other parts and assemblies.
- Grappling with high manufacturing costs due to tight tolerances.

These problems are the result of:

- An unclear definition of product and process requirements and a non-optimal use of measurement data.
- Specialized routines needed for tolerance analysis of non-rigid parts compliant assembly

Product design dimensional specification provide estimates of what the next process will require to ultimately produce desired final product specification. Tolerance analysis plays essential role for estimation of final variation. Engineers need well-defined dimensional engineering process that enables the collection and analysis of relevant, meaningful variation measurements.

This paper introduces how Dimensional Engineering (DE) process and the simulation-based tolerance analysis used in the sheet metal assembly process. A compliant part tolerance analysis is applied to calculate the flexible parts' key product characteristics (KPC) error. The case study example describes using 3DCs in predicting the effects of variations and its impact on compliant assembly. Apply a closed-loop design optimizing approach in tolerance design.

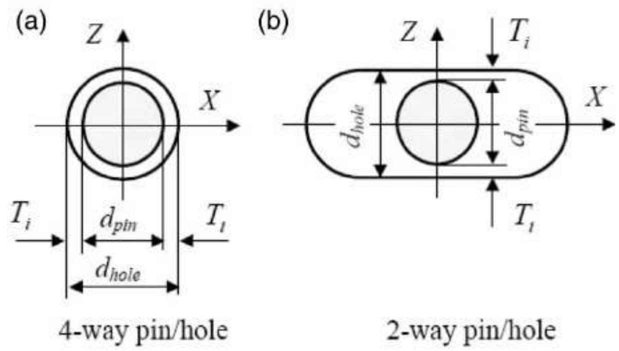


Fig. 1: 4- way and 2-way constrains [7].

2. RELATED WORKS

2.1. Tolerance Analysis for Sheet Metal Assembly

Several key characteristics of the assembly processes have great impact on the dimensional quality of the automotive body assembly. These characteristics include product characteristics such as the part geometry and part-to-part joint functions as well as process characteristics such as part locating elements and fixture locating layout.

The different positioning datum and process have great influence to the final assembling accuracy. Different datum selection have different tolerance analysis model. With the help of evaluation function of assembly quality, one can choose the most suitable process for the particular case of the sheet metal part assembly and assembly process.

Various research efforts have previously been made into the development of diagnostic methodologies for BIW assembly processes. Diagnostic approaches for single fault of fixture failures in assembly processes were proposed by Ceglarek and Shi [1]. Wang and Nagarkar [2], han and Ceglarek [3] and Khan et al.[4] studied the locator and sensor placement for the automated coordinate checking fixtures and assembly systems, respectively, for rigid parts. The modeling and diagnosis of sheet metal assembly considering the compliant characteristics such as the part-to-part interferences and the part fabrication errors has been studied. Chang and Gossard [5] studied the impacts of compliant non-ideal parts and locators on the CAD modeling. A diagnostic approach was developed based on the beam model and the principal component analysis (PCA) to isolate single fault in compliant assemblies [6].

In placing a sheet metal part to the other part has much more rigidity which usually be considered as fixture, the exact location of the part with respect to the fixture may vary randomly, due to pin/hole tolerances. Normally we adopt N- 2-1 locating scheme on the fixture components to ensure the stability. We pick 2 hole-pin fitting as the primary locators. Part is constrained in the fixture initial in a 3-2-1 fashion, fixture keeps part from rigid movement. To locate the part in this fashion, a 4-way locator, a 2-way locator and an NC block with clamp is needed. Fig. 1 shows 2-way and 4-way locators. Normally, we take the 4-way pin/hole as the primary join. This Figure also shows the tolerance between the pin/hole pair.

2.2. Simulation based Tolerance Design

Computer aided tolerance analysis (CAT) is widely used in the process of product development now. CAT allow engineers to appraise design, fabrication and assembly robustness by evaluating GD&T, tooling and build sequencing – all before production. They produce 3D-model-based tolerance simulations that identify areas of concern, potential failure rates, and statistical results, such as percent out of specification, for each measurement. Sensitivity analyses review each tolerance as it relates to each measurement and identify its percentage contribution or effects on each measurement.

A commercial software solutions, 3DCs, has an extensive set of tools and features that provide great flexibility to the engineering analyst allowing both dynamic and static models to be analyzed. With the help of this analyzing tool, we can improve product quality by validating the assembly parts fit and function together. The characteristics of 3DCs are as follows [8].

- **Flexible Assembly Compatibility** - Specialized routines developed for non-rigid parts.
- **Four Types of Analysis Outputs** - Monte Carlo Simulation, High-Low-Mean (Sensitivity Analysis), Geo Factor Analysis and Worst Case analysis.
- **Evaluate Geometric Factors** - Evaluate geometric factors to enhance the robustness of designs.
- **Identify Contributors** - Localize tolerances and assembly processes responsible for variation.
- **Unique Kinematic Solver** - Solve over-constrained assemblies
- **FEA Compliant Modeler**- Simulate deformation within the virtual assembly process

Advanced Analyzer- Quickly view and change tolerances in a graphical interactive matrix and view new analysis results from a global perspective instantly

3. TOLERANCE OPTIMIZATION FOR COMPLIANT ASSEMBLY

3.1. Sheet Metal Assembly Tolerance Analysis

Tolerance analysis is a powerful tool used to simulate manufacturing and assembly processes and predict amounts and causes of variation. It reduces the negative impact of variation on product dimensional quality.

Tolerance analysis allows the user to visualize the variation for any component or assembly, consisting of any material, through virtual simulation. Literally thousands of assemblies can be built in a virtual environment and analyzed for dimensional integrity in just minutes. Engineers can look closely at variations, particularly in critical areas of clearance, interference, flushness, angle and location.

Many parameters influence the final deviation in a sheet metal assembly. Some of these are due to unavoidable part or tooling errors. However, even without any part or tooling, errors may develop due to random positioning of the part in the fixture within the specified tolerance between locator pin and hole. Therefore, one needs an analysis tool which estimates the influence of tolerance of pin/hole on the final deviation. Such tool should be able to calculate the sensitivity of the final deviation to each tolerance, and let the designer to determine which tolerance has the largest effect on the final deviation and thus, reduce it, accordingly.

In this work, a simulation based analysis method is used for sheet metal assemblies, which examines:

- The effect pin/hole tolerance on final variation
- The effect of locator position on propagation of error

3.2. Simulation based Dimensional Engineering

A manufacturer's ability to achieve required assembly tolerances is often compromised by the complexity of managing many part tolerances within a moving assembly. Variation analysis is a critical part of determining proper assembly, tooling, and manufacturing processes [9].

In a closed-loop dimensional engineering process, as shown in Fig 2, dimensional data reports are generated as the product enters preproduction and initial runs begin. Engineers refer to the reports and check key points to ensure that measurement plans are being followed and that end-products achieve the tolerances expected based on the results of all prior steps in the dimensional engineering process. Based on these results, they are able to conduct root cause analyses of any quality issues. If the end-products are not achieving the tolerances expected, engineers can "loop back" to find out where problems originated and either resolve any issues or adjust build objectives and strategies as needed.

This DE system also drives product quality all the way from design engineering to production. Pulling together tolerance analysis tools with quality management module enable manufacturers to make timely and complete use of a vast amount of inspection data.

Additionally, it enables best practices to be validated, captured and reused on future programs,

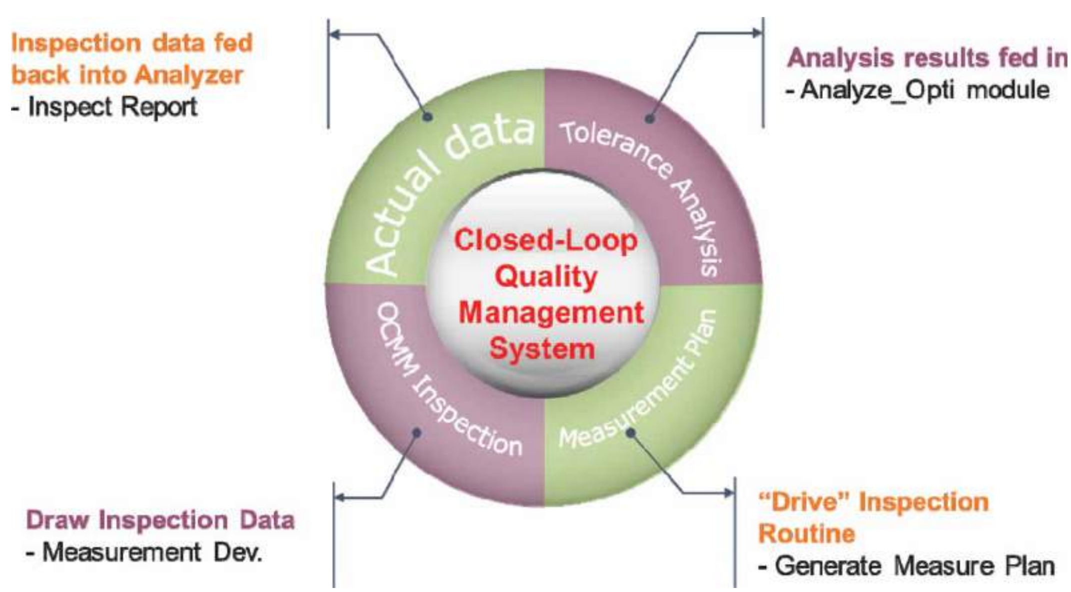


Fig. 2: Closed-Loop DE Process.

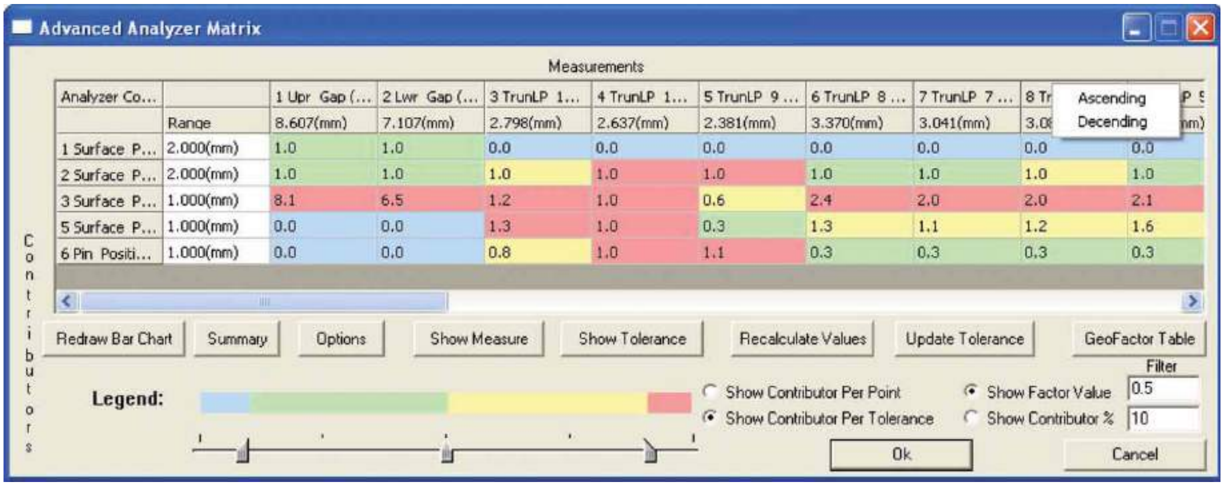


Fig. 3: Advanced Analysis Optimization (AAO) matrix [7].

for both engineering simulation and manufacturing. The intelligence gathered through this system helps engineers discovering ways to reuse existing and proven manufacturing process elements on new and re-design programs.

3.3. Computer Aided Tolerance Analysis

When locating sheet metal part to fixture, consider both the assembly parts as rigid body to calculate the effect of the primary (4-way constrain) and secondary(2-way constrain) pin/hole locating variation to the final product deviation compared to its nominal values. After running the simulation for probably schemes, one can determine and choose the optimized selection via comparing the allowed tolerance of the pin/hole pairs' position. For this purpose, the probabilistic design system OPTIMIZE_ANALYSIS is used in this stage.

- An equation based analysis output that precisely identifies the amount and source of variation within an assembly. 3DCS Analyzer creates an equation of the entire 3DCS model and displays the inputs (*contributors/tolerances*) and outputs (*measurement results*) and their relationships (*Coefficients of Influence*) in a graphical interactive matrix.

  Tolerance Range changes can be made in a graphical interactive matrix providing instantaneous feedback of updated results.
- Measurement values are equal to the Geo Factor's calculated 6 Sigma values. The 6 Sigma basically equals the Standard Dev. of the Range times the Geo Factor times 6 (6 Sigma). This is a simplified equation for linear tolerances.

Using the Advanced Analysis Optimization (AAO) matrix as showed in Fig. 3, the designer can get the best-fit scenario:

- Show Contributors Per Point: Displays the individual Geometric Factor coefficient for each point/feature in the given tolerance. The benefit of this mode is to highlight the individual point/feature with a high coefficient within the given tolerance.
- Show Contributors Per Tolerance: Combines all the individual point/feature Geometric Factor coefficients of the given tolerance by a RSS. The benefit of this mode is to observe the combined coefficient of that tolerance while minimizing the rows in the Analyzer Matrix.

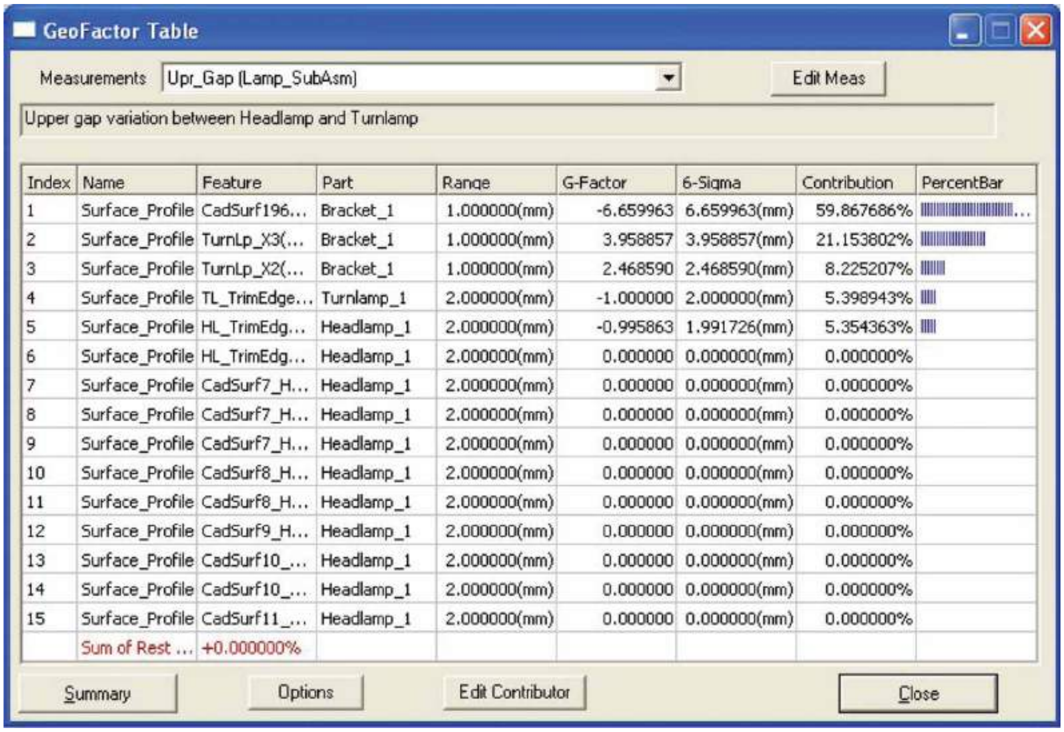
It aids in understanding the effect of coefficients on multiple measurements at once. If a coefficient that shows up red in multiple measurements, this is a tolerance that is sensitive to the system and should be addressed with caution. The legend takes the overall spread of the coefficient values and splits them into percentages based on the coefficient range. This range is calculated using the absolute max and min Geometric Factor coefficient values of the entire model (all measurements are taken into account) as shown in Fig. 4. Then the color-coding of the individual coefficient values are determined per measurement.

3.4. Compliant Assembly Tolerance Modeling

We consider the sheet metal part as the flexible (non-rigid) component and use the COMPLIANT module to analyze the tolerance by adopting N- 2-1 locating scheme on the fixture components.

Key points are identified within the design which wants to be controlled closely. For example, key points typically exist where a door fits to a body or a hood meets a side panel. All parties involved focus on holding these points precisely as the design moves into manufacturing.

While 3DCS can predict the variation of hundreds of points in the design stage, the number of points



Index	Name	Feature	Part	Range	G-Factor	6-Sigma	Contribution	PercentBar
1	Surface_Profile	CadSurf196...	Bracket_1	1.000000(mm)	-6.659963	6.659963(mm)	59.867686%	
2	Surface_Profile	TurnLp_X3(...	Bracket_1	1.000000(mm)	3.958857	3.958857(mm)	21.153802%	
3	Surface_Profile	TurnLp_X2(...	Bracket_1	1.000000(mm)	2.468590	2.468590(mm)	8.225207%	
4	Surface_Profile	TL_TrimEdge...	Turnlamp_1	2.000000(mm)	-1.000000	2.000000(mm)	5.398943%	
5	Surface_Profile	HL_TrimEdg...	Headlamp_1	2.000000(mm)	-0.995863	1.991726(mm)	5.354363%	
6	Surface_Profile	HL_TrimEdg...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
7	Surface_Profile	CadSurf7_H...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
8	Surface_Profile	CadSurf7_H...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
9	Surface_Profile	CadSurf7_H...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
10	Surface_Profile	CadSurf8_H...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
11	Surface_Profile	CadSurf8_H...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
12	Surface_Profile	CadSurf9_H...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
13	Surface_Profile	CadSurf10_...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
14	Surface_Profile	CadSurf10_...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
15	Surface_Profile	CadSurf11_...	Headlamp_1	2.000000(mm)	0.000000	0.000000(mm)	0.000000%	
	Sum of Rest ...	+0.000000%						

Fig. 4: Geometric Factor Table [7].

that we can actually check must be limited for the time consume considering.

3.5. Manufacturing Data Incorporated Optimization Approach

To realize the full potential of simulation based tolerance design, it's necessary to incorporate quality inspection data back into the tolerance simulation model and compare a simulation with reality. A suite of software solutions offered by Dimensional Control Systems, Inc. (DCS) pulls together tolerance analysis software (3DCS) with quality management software (QDM-Web) enabling manufacturers to make timely and complete use of a vast amount of inspection data. The web-based QDM delivers quality data from the on-site metrology devices.

It enables engineers to correlate the theoretical tolerance analysis results produced during simulation to the actual as-built results determined at downstream stages of the quality process. Based on correlations, the as-designed simulation parameters can be validated, or the as-designed simulation parameters can be adjusted to more closely align to production process capabilities.

The comprehensive dimensional engineering process allows fit, finish, and function to be analyzed across the entire design-build lifecycle. Multiple solutions can be tried through visual simulation then validated through automated as-built reporting.

4. CASE STUDY

In this part, we will discuss a real engineering tolerance analysis case. It includes both compliant assembly of the sheet metal part and the tolerance optimization consideration.

4.1. Assembly components

This assembly case consists of six parts. The rear frame wall of BIW can be treated as fixture since its rigidity.

4.2. Tolerance Analysis Modeling

4.2.1. Assembly structure

The assembly components are presented in Fig. 5. Their relationship is shown in Fig. 6.

4.2.2. Assembly part locating strategies

The definition of the way parts be located and held are shown as follows.

- Rear wall frame act as the fixture of assembly which has pin or pin-hole features for the locating features need for the other part.
- Each of the other sheet metal parts has two primary pin-holes, one 4-way and one 2-way pinhole work as locating features, for locating as the KPC points.

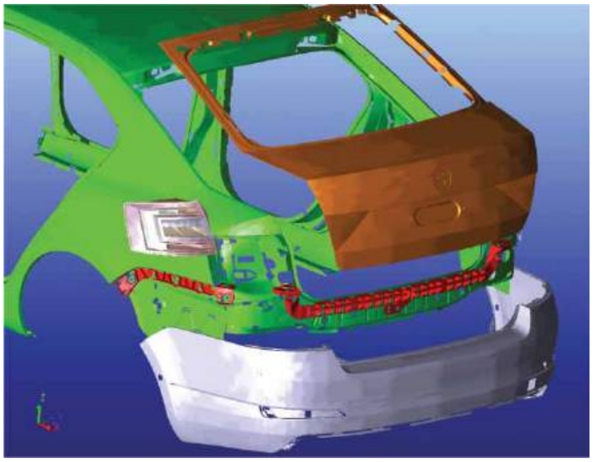


Fig. 5: Assembly model of the case study.

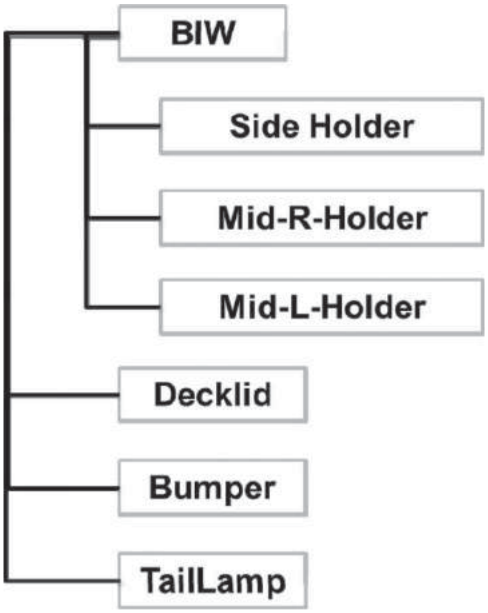


Fig. 6: Part assembly relationship.

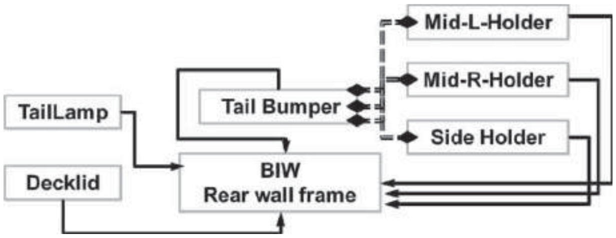


Fig. 7: Assembly relationship.

The assembly relationship can be presented by Fig. 7 as follow. The full lines indicate the constrains of DOF (Degree of Freedom). The dash lines present the over-constrains.

4.2.3. *Constrain definition*

Constrain definition of components is shown in Fig. 8.

- Tail Bumper to rear wall frame – pin/hole locating
- Holders to rear wall frame – pin/hole locating
- Tail Bumper to Side holder – clip assembly
- Tail Bumper to Mid-holder – clip assembly

4.2.4. *Inspection plan*

Tolerance of the matching zone formed by the assembled tail bumper and side-panel is set as the inspection area. Measurement point sets are defined for the Flash and Gap (F/G) of the matching area which is shown in Fig. 9.

By removing the unnecessary details, a simplified model of the assembly is created for reducing the computing time. Fig. 10 shows the simplified analysis model of this assembly which is established in 3DCs.

4.3. GD&T Requirements

Since this case is a real manufacturing product, we just duplicate the original engineering GD&T strategies as the initial setting of the tolerance simulation parameters, like datum locators and related dimensions, etc.

The assembly quality requirement is shown in Tab. 1.

4.4. Tolerance Analysis

After running the simulation of tolerance analyze, the result shows the initial dimensional setting can basically satisfy the requirement of engineering. But there are some excess vibration observed in some matching zone of the assembly, especially in the matching of side panel and tail bumper.

Action should be taken to improve the assembly quality of these areas. Deeply research the analyze result and the engineering construction of the assembly, we can find the impact factors of the final variation which is descripted as follows.

The position strategy of assembly part position

- Datum locator position.
- Tolerance of the locating pin-hole.

The rigid assumption of the tail bumper component

- Part flexibility affect ignoring.
- Redundant constrain of the assembly process

4.5. Root Cause Conduct

Conducting root cause analysis, we “loop back” to see where the problem originated and try to find resolve

Fig. 8: Constrain definition: (a) Tail Bumper to rear wall frame. (b) Tail Bumper to Side holder. (c) Tail Bumper to Mid-holder.

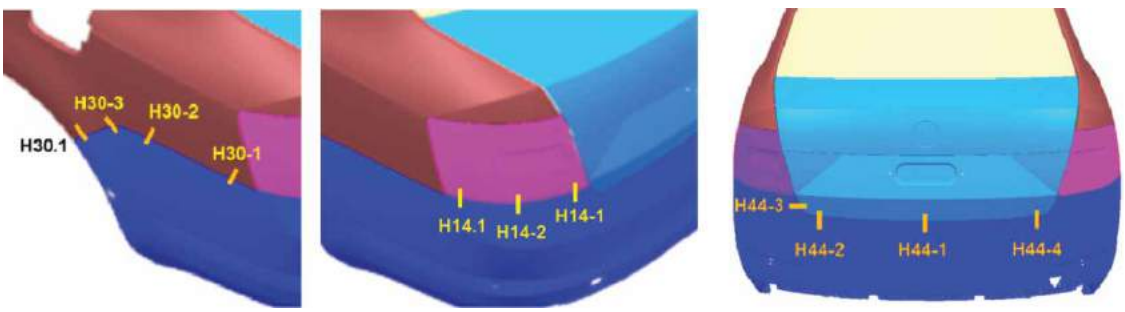


Fig. 9: Inspection zone: (a) matching F/G of side panel and tail bumper (b) matching F/G of tail bumper and tail light bottom edge (c) matching F/G of tail bumper and deck lid.

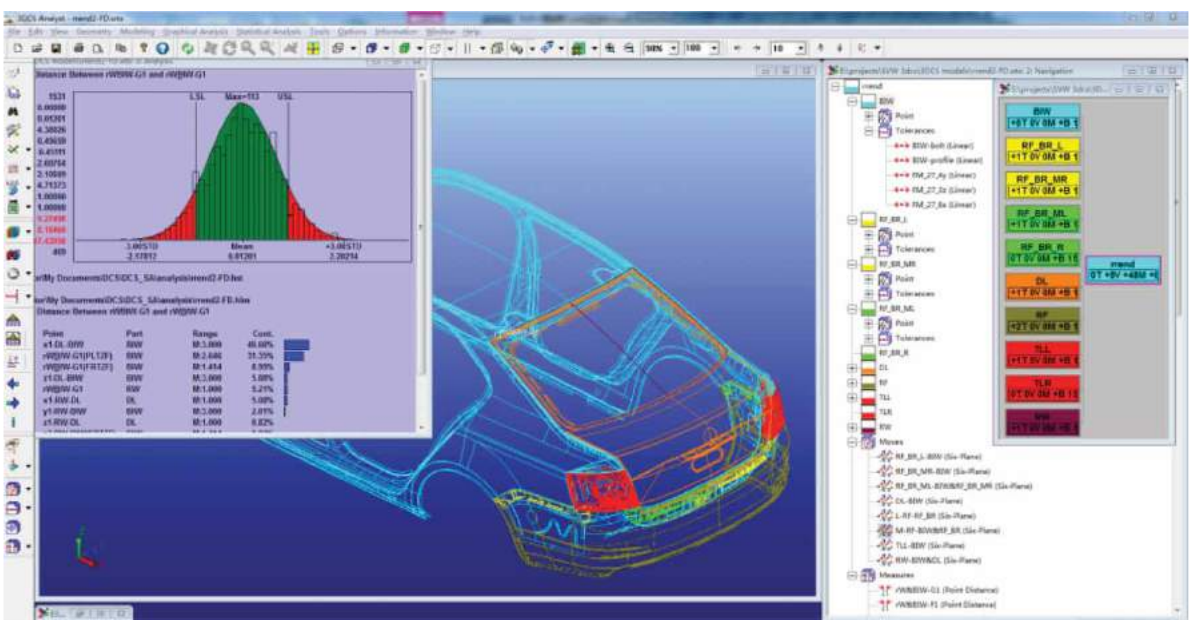


Fig. 10: Tolerance analysis model.

strategies. In this stage, only the tolerance parameter of the locating pin-hole pair and the layout of datum locator can be handled. Besides the adjusting of the locator tolerance, the datum locator strategy can be only based on empirical trial.

4.6. Optimization Strategies

4.6.1. Compliant assembly tolerance modeling

Treat the tail bumper as the flexible part. Use compliant model to simulate the tolerance. The mesh model of tail bumper is shown in Fig. 11.

1.Tail bumper/BIW(Flash)	0–0.5 mm
2.Tail bumper/BIW(Gap)	±0.5 mm
3. Tail bumper/Tail Light(Flash/Gap)	±0.5 mm
4. Tail bumper/Deck lid(Flash/Gap)	±0.5 mm

Tab. 1: Design quality requirement.

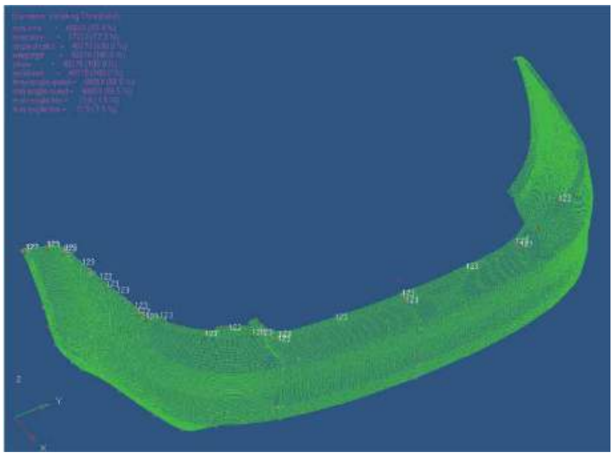


Fig. 11: Tail bumper FE model.

Define the assembly over-constrain condition as following FE load-case.

- Tail Bumper to Side holder – clamp-coincident (Position 1), clamp-soft 1DOF (Position 2∼9)
- Tail Bumper to Mid-holder – clamp-soft 1DOF

Input FE mesh and constrain load-case in the analyzing model and adopt the COMPLIANT module to run the simulation.

4.6.2. *Inspection data incorporation*

Using Quality Data Management System (QDM) of 3DCs can automatically connect the measuring facilities to collect the manufacturing quality data, like inspection data, for tolerance analysis core quickly locate tolerances and assembly processes responsible for variation. Comparing the calculated results with the actual inspection data, we can monitor the root cause of variations and discover the way to adjust the simulation parameters, like the initial tolerance of the pin-hole or even the location layout.

4.7. Results

We used the historical manufacturing inspection data to compare the simulation result which we get from the compliant assembly tolerance analyze model. It validate the correctness of the constrain parameter setting in the model.

According to the real engineering and manufacturing condition, we finally get limited number of potential dimensional strategies. Simulation results help us find the tolerance specification of the optimized locators' layout scheme of tail bumper and holders. It satisfied the engineering dimensional requirement. Achieve the solution of the sheet metal assembly. The optimized locator position layout and datum scheme of the assembly parts are shown in Fig. 12 and Fig. 13.

The SPC reports of the measurement data of the initial dimension scheme and optimized scheme are shown in Fig. 14. By deep research of the measurement data, we can conclude that after adjusting the position of locator layout and datum scheme, the quality condition of this sheet metal assembly get improved. The passing rate of some particular inspection points obviously elevated.

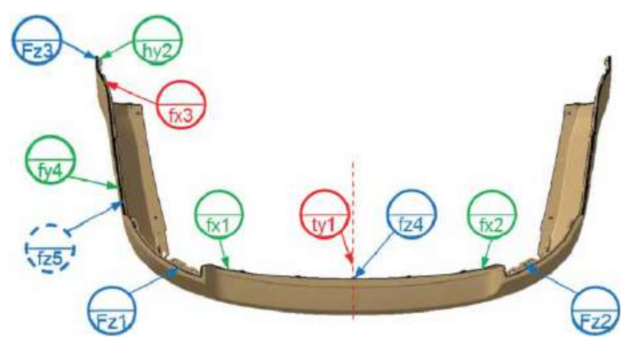
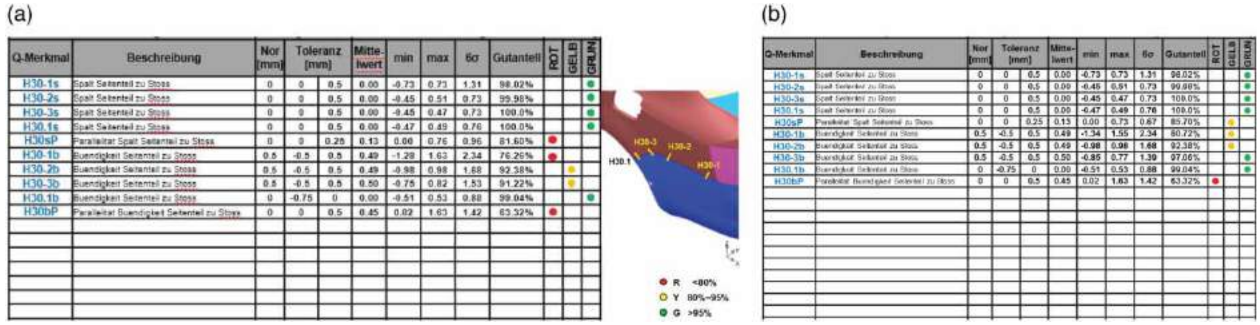


Fig. 13: Optimized Layout and datum scheme of tail bumper.

Fig. 12: Optimized locating layout of holders: (a) locating position of Mid-holder (b) locating position of side holder.



(a)

Q-Merkmal	Beschreibung	Nor [mm]	Toleranz [mm]		Mittelwert	min	max	6σ	Gutanteil	ROT	GELB	GRÜN
H30-1s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.73	0.73	1.31	98.02%			●
H30-2s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.45	0.51	0.73	99.98%			●
H30-3s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.45	0.47	0.73	100.0%			●
H30.1s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.47	0.49	0.76	100.0%			●
H30sP	Parallelitat Spalt Seitenteil zu Stoss	0	0	0.25	0.13	0.00	0.76	0.96	81.60%	●		
H30-1b	Buendigkeit Seitenteil zu Stoss	0.5	-0.5	0.5	0.49	-1.28	1.63	2.34	76.26%	●		
H30-2b	Buendigkeit Seitenteil zu Stoss	0.5	-0.5	0.5	0.49	-0.98	0.98	1.68	92.38%		●	
H30-3b	Buendigkeit Seitenteil zu Stoss	0.5	-0.5	0.5	0.50	-0.75	0.82	1.53	91.22%		●	
H30.1b	Buendigkeit Seitenteil zu Stoss	0	-0.75	0	0.00	-0.51	0.53	0.88	99.04%			●
H30bP	Parallelitat Buendigkeit Seitenteil zu Stoss	0	0	0.5	0.45	0.02	1.63	1.42	63.32%	●		

(b)

Q-Merkmal	Beschreibung	Nor [mm]	Toleranz [mm]		Mittelwert	min	max	6σ	Gutanteil	ROT	GELB	GRÜN
H30-1s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.73	0.73	1.31	98.02%			●
H30-2s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.45	0.51	0.73	99.88%			●
H30-3s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.45	0.47	0.73	100.0%			●
H30.1s	Spalt Seitenteil zu Stoss	0	0	0.5	0.00	-0.47	0.49	0.76	100.0%			●
H30sP	Parallelitat Spalt Seitenteil zu Stoss	0	0	0.25	0.13	0.00	0.73	0.67	85.70%		●	
H30-1b	Buendigkeit Seitenteil zu Stoss	0.5	-0.5	0.5	0.49	-1.34	1.55	2.34	80.72%		●	
H30-2b	Buendigkeit Seitenteil zu Stoss	0.5	-0.5	0.5	0.49	-0.98	0.98	1.68	92.38%		●	
H30-3b	Buendigkeit Seitenteil zu Stoss	0.5	-0.5	0.5	0.50	-0.85	0.77	1.39	97.06%			●
H30.1b	Buendigkeit Seitenteil zu Stoss	0	-0.75	0	0.00	-0.51	0.53	0.88	99.04%			●
H30bP	Parallelitat Buendigkeit Seitenteil zu Stoss	0	0	0.5	0.45	0.02	1.83	1.42	63.32%	●		

Fig. 14: SPC measurement data reports of the side-panel/tail bumper: (a) Report of the initial dimension scheme (b) Report of the optimized scheme.

5. SUMMARY

The aim of this paper is to using simulation-based dimensional engineering (DE), tolerance analysis and FE method to identify the key points that most affect the fit in the compliant assembly process of sheet metal. Following the closed-loop which incorporated with manufacturing data, we can validate the correctness of the tolerance analyze model. Results of a case study were presented tolerance optimization which demonstrates the effectiveness of proposed approach in tolerance analysis of compliant assemblies.

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