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Efficient Spot Welding Sequence Simulation in Compliant Variation Simulation

Geometrical variation is one of the sources of quality issues in a product. Spot welding is an operation that impacts the final geometrical variation of a sheet metal assembly considerably. Evaluating the outcome of the assembly, considering the existing geometrical variation between the components, can be achieved using the method of influence coefficients (MICs), based on the finite element method (FEM). The sequence with which the spot welding operation is performed influences the final geometrical deformations of the assembly. Finding the optimal sequence that results in the minimum geometrical deformation is a combinatorial problem that is experimentally and computationally expensive. Traditionally, spot welding sequence optimization strategies have been to simulate the geometrical variation of the spot-welded assembly after the assembly has been positioned in an inspection fixture. In this approach, the calculation of deformation after springback is one of the most time-consuming steps. In this paper, a method is proposed where the springback calculation in the inspection fixture is bypassed during the sequence evaluation. The results show a significant correlation between the proposed method of weld relative displacements evaluation in the assembly fixture and the assembly deformation in the inspection fixture. Evaluating the relative weld displacement makes each assembly simulation less time-consuming, and thereby, sequence optimization time can be reduced by up to 30%, compared to the traditional approach. [DOI: 10.1115/1.4049654]

Keywords: spot welding, sequence, optimization, compliant variation simulation, deformation

1 Introduction

Geometrical variation is the source of the aesthetic and functional problems in the assemblies. The disturbances in the assembly process, and individual components variation, lead to a non-nominal assembly. For compliant assemblies, the joining process is among the critical processes inducing geometrical variation in the assemblies. Controlling the sources of variation, such as joining parameters, is a common challenge in the manufacturing industry [1]. To tackle this challenge, recent studies have focused on digital twin development used for geometry assurance activities [2,3] during the product development phases [4–6]. Therefore, the role of the simulations are becoming more prominent enhancing the accuracy of the digital twins, specially in joining simulations. The sequence with which the assembly is joined has shown to have a considerable effect on the final geometrical outcome [7–10]. It has also been shown that considering the sequence of welding increases the accuracy of the joining simulations results [11]. To identify the best joining sequence for the sheet metal assemblies, using compliant variation simulation is a combinatorial problem. This problem has a costly function evaluation, requiring time-consuming simulations. The number of possible alternatives to perform welding increases factorially by increasing the number of welds. The need for a more time-efficient and accurate simulation method to determine the optimal joining sequence is preeminent.

1.1 Compliant Variation Simulation. Compliant variation simulation is introduced to evaluate the sheet metal assemblies, considering the variation of the components' geometry in computer-aided tolerancing (CAT) tools [2,12]. In this approach, FEM and Monte Carlo (MC) simulations are combined to evaluate the outcome of the assembly considering the geometrical variation in the components, from the corresponding tolerance distributions, while they are being held in a fixture [12,13]. The traditional approach to simulate the geometrical variation of compliant assemblies is direct Monte Carlo (DMC), where for each Monte Carlo iteration, a full FEM is performed. To further increase the time efficiency of the method, the method of influence coefficients is introduced [12,14]. MIC is an exact method, similar to DMC, building linear relationships between the part deviation and acting forces on the assembly. The response of the assembly to these forces is saved in a sensitivity matrix and associated with the part deviations. The MIC approach is complemented by contact modeling to increase the accuracy of the simulation. The contact modeling avoids the parts to penetrate in the adjacent areas [15–19]. With the small displacements assumption, elastic material, and neglecting the effect of heat, the spot welding process is introduced to the variation simulation [12]. Based on the approach a multi-station assembly perspective has also been developed [20]. For continuous welding application, welding distortion has been incorporated into compliant variation simulation [21,22]. To evaluate the effect of

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joining sequence, the springback of the assembly after each joint is calculated [11,23]. The MIC and contact modeling for evaluating the spot-welded assemblies has been further improved by removing the intermediate springback calculations [24]. With the state of the art variation simulation, a noticeable fraction of the simulation time is dedicated to springback calculation in the inspection fixture, with respect to the specified joining sequence. In this paper, a new time-efficient method to simulate the geometrical outcome of the assemblies with respect to the joining sequences is proposed.

1.2 Spot Welding Sequence Analysis.

Determining the optimal sequence of welds is an NP-hard combinatorial problem. Physical experimentation for this reason is economically infeasible. Therefore, the optimization algorithms are often combined with a simulation tool for assembly evaluation [25,26]. With the state of the art variation simulation, or other FEM-based simulations, the most time-consuming step of the optimization is the assembly evaluation [8]. To find the optimal sequence with the minimal number of assembly simulations has been addressed in previous studies [9,27]. Algorithms based on a random search, such as the genetic algorithm, have been studied extensively [7,25]. However, these methods are highly dependent on the number of assembly evaluations performed. For larger population sizes, larger number of assembly simulations are required. More time-efficient rule-based approaches have been introduced using the compliant variation simulation as an evaluator [9]. A surrogate modeling approach has also been introduced, together with an efficient sampling strategy, using MIC and contact modeling [27]. Deploying compliant variation simulation as an evaluator, a novel stepwise algorithm for joining sequence optimization is also introduced [28]. The previous studies have focused on reducing the number of evaluations by the compliant variation simulation. In this paper, the perspective of reducing each assembly simulation time, from the compliant variation simulation, is taken into consideration.

1.3 Scope of the Paper.

Spot welding sequence optimization is a time-consuming task. Evaluating the assembly deformation with respect to the part deviations is performed with compliant variation simulation. In this simulation, springback calculation, while the part is not over-constrained in the inspection fixture, is one of the time-consuming steps. To optimize the sequence of welds, a large number of sequences need to be evaluated. Therefore, a more efficient approach for variation simulation with respect to welding sequences is searched for. In this paper, an efficient variation simulation approach for welding sequence optimization is proposed. Section 1 provided an introduction to the problem. Section 2 presents the proposed approach followed by the presentation of the reference assemblies in Sec. 3. Section 4 presents the evaluation of the approach on the reference assemblies. Finally, in Sec. 5, the conclusions are drawn based on the results achieved, and the future research scope is presented.

2 Proposed Approach

In this section, the proposed variation simulation approach for the spot welded assemblies, considering the sequence of welding, is introduced. The standard, state of the art, variation simulation is introduced in Sec. 2.1. Sections 2.2–2.5 present the proposed approach.

2.1 Assembly Simulation Steps.

There are two aspects constructing the final assembly deviation. These are, part deviations from previous manufacturing steps, $\boldsymbol{u}^{dev}$, and assembly deformation $\boldsymbol{u}$. The overall simulation approach is presented in Fig. 1. The assembly model is built based on the FEM and MIC. Sensitivity matrices are built as the response to a unit disturbance. In the Monte Carlo loop, part deviations are applied to the nodes, and contact modeling is performed, avoiding penetration in the adjacent areas. After a number of iterations, the assembly variation is achieved. The steps below describe how to calculate the assembly deformation while the part is held in the assembly fixture.

The general steps of the assembly modeling in variation simulation, following the formulation in Ref. [29], include the following:

(1) Positioning parts and clamping in the fixture.
(2) Derive the clamping, contact, and joining forces, $\boldsymbol{f}_{cl}^{\boldsymbol{0}}$, $\boldsymbol{f}_{c}^{\boldsymbol{0}}$, and $\boldsymbol{f}_{w}^{\boldsymbol{0}}$, respectively. Here, contact modeling is used. The overview of the applied forces and reactions in the nominal assembly is shown in Fig. 2(*a*). An example where penetration occurs and the contact forces are applied is visualized in Fig. 2(*b*). It has to be noted that $\boldsymbol{f}_{w}^{\boldsymbol{0}}$ and $\boldsymbol{f}_{c}^{\boldsymbol{0}}$ can be calculated directly using the contact modeling, but $\boldsymbol{f}_{cl}^{\boldsymbol{0}}$ is calculated successively [29]. Expressing the initial stiffness matrix[2] with $\boldsymbol{K}^{\boldsymbol{0}}$, and the assembly deformation as $\boldsymbol{u}^{\boldsymbol{0}}$, then the following holds:

$$\boldsymbol{K}^{\boldsymbol{0}}\boldsymbol{u}^{\boldsymbol{0}} = \boldsymbol{f}_{cl}^{\boldsymbol{0}} + \boldsymbol{f}_{c}^{\boldsymbol{0}} + \boldsymbol{f}_{w}^{\boldsymbol{0}} \tag{1}$$

Since the number of non-zero elements in $\boldsymbol{f}_{cl}^{\boldsymbol{0}}, \boldsymbol{f}_{c}^{\boldsymbol{0}}$, and $\boldsymbol{f}_{w}^{\boldsymbol{0}}$ are typically relatively small, the corresponding sensitivity matrix, which consists of the corresponding column in the inverse matrix, is pre-calculated. The relation $\boldsymbol{S}^{\boldsymbol{0}} = [\boldsymbol{K}^{\boldsymbol{0}}]^{-1}$ holds only with respect to the relevant rows [12]. Hence, the following can be written as follows:

$$\boldsymbol{u}^{\boldsymbol{0}} = \boldsymbol{S}^{\boldsymbol{0}}(\boldsymbol{f}_{cl}^{\boldsymbol{0}} + \boldsymbol{f}_{c}^{\boldsymbol{0}} + \boldsymbol{f}_{w}^{\boldsymbol{0}}) \tag{2}$$

To achieve the contact equilibrium, the contact forces are calculated using quadratic programming [17]. Finding the contact forces is a non-linear problem imposing non-linear behavior to the equation above.
(3) Joining parts through adding stiff beams, locking all the degrees-of-freedom between the weld pairs.[3] Expressing the updated stiffness modifier as Δ, that is the stiffness of the beam, then

$$(\boldsymbol{K}^{\boldsymbol{0}} + \Delta\boldsymbol{K}^{\boldsymbol{0}})\boldsymbol{u}^{\boldsymbol{0}} \equiv \boldsymbol{K}^{\boldsymbol{1}}\boldsymbol{u}^{\boldsymbol{0}} = \boldsymbol{f}_{cl}^{\boldsymbol{0}} + \boldsymbol{f}_{c}^{\boldsymbol{0}} \tag{3}$$

or

$$\boldsymbol{u}^{\boldsymbol{0}} = \boldsymbol{S}^{\boldsymbol{1}}(\boldsymbol{f}_{cl}^{\boldsymbol{0}} + \boldsymbol{f}_{c}^{\boldsymbol{0}}) \tag{4}$$

where the relation

$$\Delta\boldsymbol{K}^{\boldsymbol{0}}\boldsymbol{u}^{\boldsymbol{0}} = -\boldsymbol{f}_{w}^{\boldsymbol{0}} \tag{5}$$

is used.
(4) Next, the contact forces are removed, and the response is calculated.[4]

$$\boldsymbol{u}_{sb}^{\boldsymbol{1}} = -\boldsymbol{S}^{\boldsymbol{1}}\boldsymbol{f}_{c} \tag{6}$$

The new penetrated state after one weld is

$$\boldsymbol{u}^{\boldsymbol{1}} = \boldsymbol{u}^{\boldsymbol{0}} + \boldsymbol{u}_{sb}^{\boldsymbol{1}} \tag{7}$$

(5) From this step, new clamping, contact, and weld forces are calculated, as in step 1, using the sensitivity matrix $\boldsymbol{S}^{\boldsymbol{1}}$.
(6) Iterate among the welds in a sequence. Using the sensitivity matrix $\boldsymbol{S}^{i}$ at each welding step i, for an assembly with n spot welds, the aggregated deformation after welding in a sequence is calculated as follows:

$$\boldsymbol{u}^{n} = \boldsymbol{u}^{\boldsymbol{0}} + \sum_{i=1}^{n} \boldsymbol{S}^{i}\boldsymbol{f}_{c}^{i} \tag{8}$$

[2]Modified to account for boundary conditions.
[3]Weld pairs is one node on each part that define where the spot weld is added.
[4]The geometry described by the deformation $\boldsymbol{u}_{sb}^{\boldsymbol{1}}$ can include penetrations. This state is purely a virtual state.

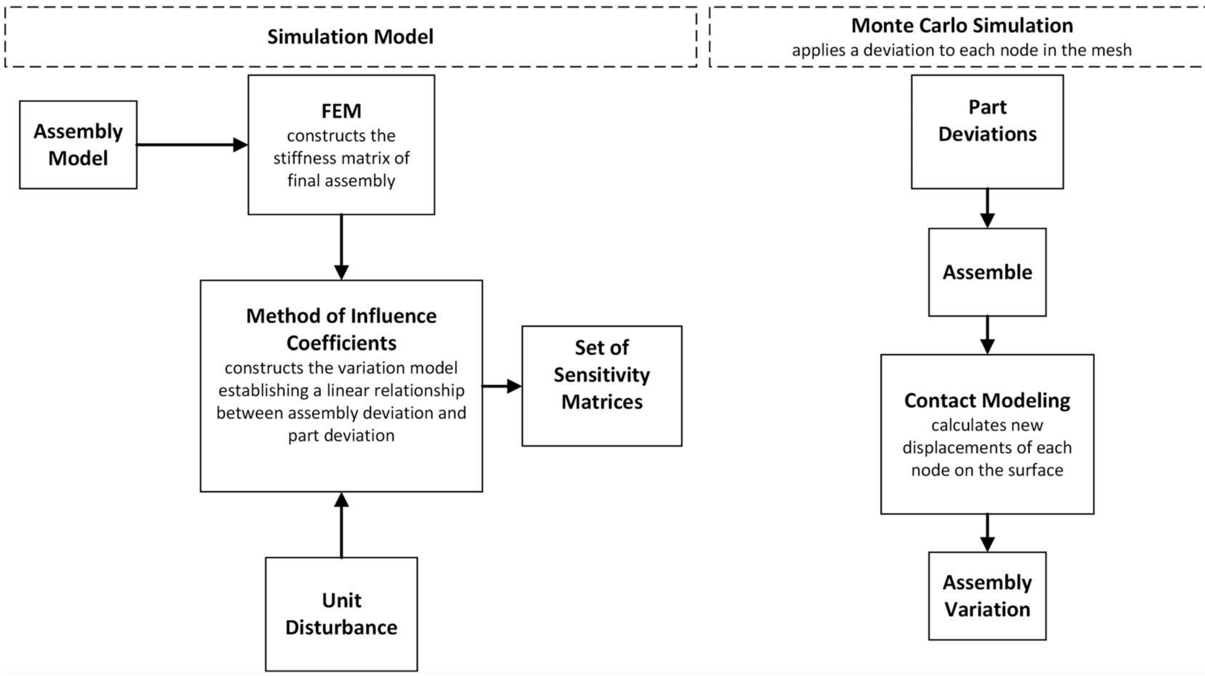

Fig. 1 Compliant variation Simulation using MIC and contact modeling

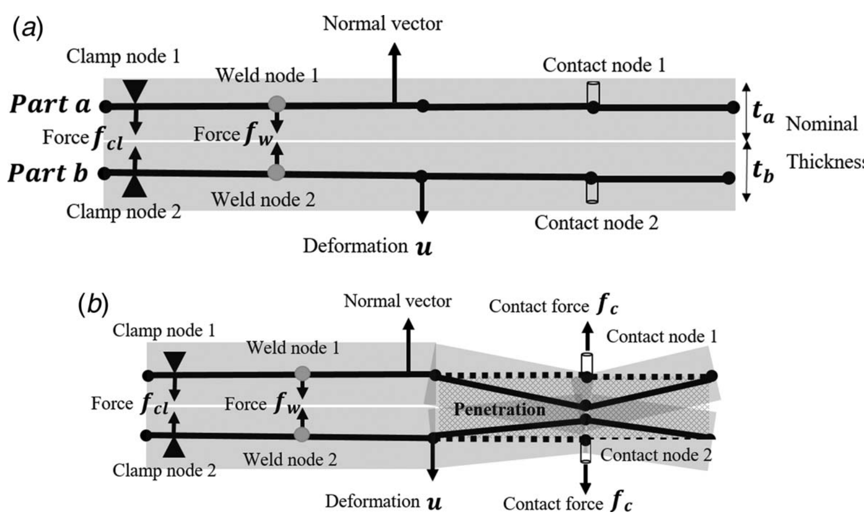

Fig. 2 Overview of the applied forces and deformation in MIC and contact modeling: (*a*) nominal assembly and (*b*) penetration state

After these steps, the assembly is typically placed in an inspection fixture, where it is not over-constrained. To calculate the final deformation in this fixture, new sensitivity matrices, a new penetration state, and new penetration forces need to be calculated.

However, assuming elasticity, which steps 1–5 above are based on, given the relative displacement in every weld pair, that is locked after welding, the final displacement can be calculated. This is achieved by positioning every part in the inspection fixture, constraining each weld pair to be in the relative displacement found during spot welding in the assembly fixture, adding corresponding beams, and calculating the final shape, including the resolved penetration by contact modeling.

Since calculating the springback in the inspection fixture is time-consuming, considering that the relative displacements are captured in the assembly fixture, this information can be used to construct the deviations in the inspection points. Finding the optimal sequence of welding with respect to these relative displacements in the assembly fixture can reveal the optimal sequence in the inspection fixture, without having to calculate the last springback step.

2.2 Relative Displacements.

For weld sequence optimization with respect to the assembly deformation, after applying n weld points, Sec. 2.1, reduced assembly simulation time is searched after. Since the assembly deformation, in the inspection fixture, depends on the assembly fixture, the relative displacements in the weld points, and the contact forces, it is expected that the sequence of welds in the assembly fixture with the smallest relative displacements in the weld points, represent the assembly with the lowest total deformation.

Figure 3 is the schematic view of the calculation procedure of weld relative displacements, d. On the left side, the current procedure is visualized. For non-nominal parts, the parts are positioned in the assembly fixture; forces are applied to mate the parts in the

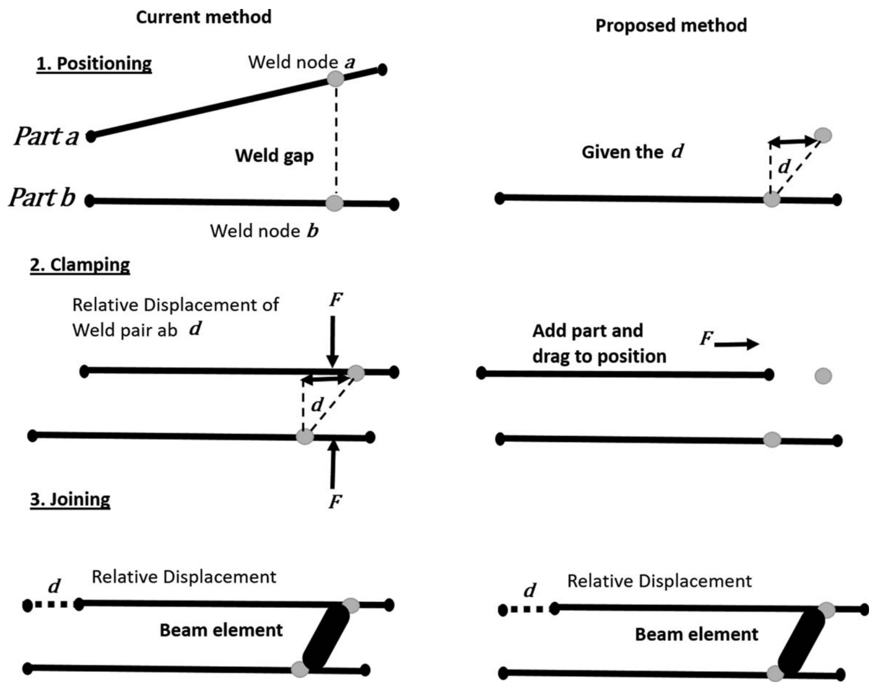

Fig. 3 Relative displacement between the weld pairs

welding nodes. These forces cause the parts to move relative to each other. Finally, to join the parts, a stiff beam element is added, locking all the degrees-of-freedom on the weld pairs together. From another perspective, if the relative displacements in the clamped position is known, it is expected that these relative displacements be directly translated to the inspection fixture. On the right side of Fig. 3, the proposed modifications are visualized. Given the relative displacements in the clamping position, the deformation after spring back can be calculated by adding a part and dragging the weld nodes to the calculated relative displacements. The joint can be defined in the calculated position. Therefore, if the relative displacements in all the welds are captured, while each weld is set in a sequence, these displacements should describe the behavior between the sequences.

2.3 Correlation and Causation. *Correlation analysis:* To show the dependency of the weld relative displacements in the assembly fixture, d, and the total assembly deformation in the inspection fixture, the correlation of the two variables are analyzed. This step is to verify the dependency of the final deformation in the inspection fixture to the weld relative displacements. The correlation analysis is not essential to perform the compliant variation simulation with the proposed approach. Let us define the total assembly deformation, $\boldsymbol{u}+\boldsymbol{u}^{dev}$ in the inspection fixture, as the root-mean-square (RMS) of the magnitude of displacements in each mesh node for a specific sequence i, as u_i. Considering that there are r nodes in the assembly, then

$$A_m^{RMS} = \sqrt{\frac{1}{r}\sum_r \|u_i^r\|^2} \tag{9}$$

A_m^{RMS} depends on the contact forces in the inspection fixture and hence is a function of the initial deviation (incoming part deviation). It also depends on the assembly fixture and relative displacements in the weld points. Now the root-sum square (RSS) of the relative displacements d for that specific sequence, i with n weld points is as follows:

$$A_d^{RSS} = \sqrt{\sum_n d_i^{n2}} \tag{10}$$

The correlation of the two is calculated as follows:

$$\rho_{A_m^{RMS},\, A_d^{RSS}} = \frac{E[(A_m^{RMS} - \mu_{A_m^{RMS}})(A_d^{RSS} - \mu_{A_d^{RSS}})]}{\sigma_{A_m^{RMS}}\sigma_{A_d^{RSS}}} \tag{11}$$

Causal inference: To verify the causation of the weld relative displacements on the deformations in the inspection fixture, the value of A_m^{RMS} and A_d^{RSS} is evaluated for a random number of sequences. An exhaustive search is performed for all the sequences, while all the other affecting parameters in the MIC and contact modeling method are kept constant. The connected scatter plot of the changes in the sequences is analyzed for each variable. Determining that the two variables behave similarly, the correlation analysis is performed to verify the significance of the dependencies. While the above correlation analysis is based on Pearson correlation, Spearman analysis, and the null hypothesis, H_0 rejecting the existing correlation between the two variable [30] are also performed. The results are discussed in Secs. 4.1.1 and 4.1.2 to point out further the significance of correlation and causation of the weld relative displacements to deformations in the inspection fixture.

Given the exact A_d^{RSS} values, the assembly can be put in any inspection fixture without recalculating all the steps mentioned in Secs. 2.1. However, to calculate A_m^{RMS} all the steps must be followed. Showing that the relative displacements in the welds and the assembly deformation measure have a significant positive correlation determines that the two measures can be used as an objective for sequence optimization interchangeably.

2.4 Sequence Optimization. Showing that the relative displacements of the assembly weld points, set in a sequence in the assembly fixture, and the total assembly deformation in the inspection fixture are highly correlated, this measure can be used as the objective of the sequence optimization. To capture the relative displacements d, the springback calculation in the inspection fixture, Fig. 3, do not need to be performed. These displacements can be captured after clamping and setting each weld in a sequence. This is a prominent advantage for sequencing, where a large fraction of the simulation time can be bypassed. The minimization of the relative displacements A_d^{RSS} among the sequences, for an assembly with n welds with the sequence $W_i = [x_1, \ldots, x_n]$, can be formulated as follows:

$$\begin{aligned} &\underset{W_i}{\text{minimize}} \quad A_d^{RSS}(W_i) \\ &\text{subject to} \quad \boldsymbol{W}:\{1, \ldots, n\} \rightarrow \{n, \ldots, 1\}, \ n \in \mathbb{N} \\ &\qquad\qquad W_i \subseteq \boldsymbol{W}, \ i \in \mathbb{N}:1 \leq i \leq |\boldsymbol{W}| \\ &\qquad\qquad W_i = \{x_{i1}, \ldots, x_{ij}\}, \ x_{ij} \in \mathbb{N}:1 \leq j \leq n \\ &\qquad\qquad |W_i| = n. \end{aligned} \tag{12}$$

Only complete permutations of 1 to n are to be considered in the solution space. To solve the optimization problem, the stepwise algorithm proposed in Ref. [28] is used. The state-space search approach in this algorithm is based on evaluation of all the possible alternatives for each sequence element, while the rest of the weld points are set. With this algorithm, the optimized sequence with respect to the assembly deformation, and weld relative displacements are derived and compared. The total optimization time using each method is also evaluated and compared.

In this perspective, the sequence that results in the minimum displacements for the whole assembly is identified. In another perspective, the assemblies' critical measurement points can also be evaluated. The next section discusses this aspect.

2.5 Critical Measurement Point Analysis. Showing that the RSS of the weld relative displacements in the assembly fixture is correlated to the RMS of the magnitude of the displacements of all the assembly nodes in the inspections fixture, they can be used interchangeably for sequence optimization. Considering one-to-one linear relationship between the two variables, it is expected that the RSS of weld relative displacements does not represent the displacement behavior of each assembly nodes in all directions. Therefore, a correlation between the displacements in the weld points and the critical measure needs to be identified. Consider the assembly of two-sheet metals with six weld points presented in Fig. 4. The behavior of the deformations of the critical measurement point in the inspection fixture needs to be related to the relative displacements of the welds in the assembly fixture. To achieve this, initially, the direction of the relative displacements of each weld for a specific sequence needs to be identified and correlated to the deformations of the measurement point, for that specific sequence.

To build such a relationship between the relative weld displacements in the assembly fixture, and the deformations in the inspection fixture, an input-output model, mapping the weld relative displacements to the deformations in the inspection fixture for the different sequences is needed. It has been shown that considering all the combinations of the initial sequence elements can reveal the behavior of changes between all the sequences [27]. Therefore, to build these models, in the first step of the optimization process [28], the deformations in the inspection fixture are captured in addition to the relative weld displacements. Using this data, a non-linear model is built, mapping the weld relative displacements to the deformations in the inspection fixture. Hence, the function Φ provides the estimate of the deformation in the inspection fixture $\hat{u}$, for the specified measure, given the relative displacements of all the weld points in different dimensions, $d_n^{x,y,z}$. Here, the reference axes for a three-dimensional Cartesian coordinate system, x, y, z, are used.

$$\hat{u} = \Phi(d_1^x, d_1^y, d_1^z, \ldots, d_n^x, d_n^y, d_n^z) \tag{13}$$

Support vector machines (SVMs) have been shown to be efficient for creating non-linear models on this type of problem [31]. Therefore, Φ is a trained SVM model. With the same formulation as Eq. (12), the minimization of Φ, subject to the relative displacements of all the welds between the sequences, is performed, and the optimal sequence is identified. Here, the first step of the optimization evaluates the deformations in the inspection fixture, and the model of the deformations with respect to the relative displacements in the assembly fixture is built. The following steps of the optimization use this model to estimate the deformations in the inspection fixture.

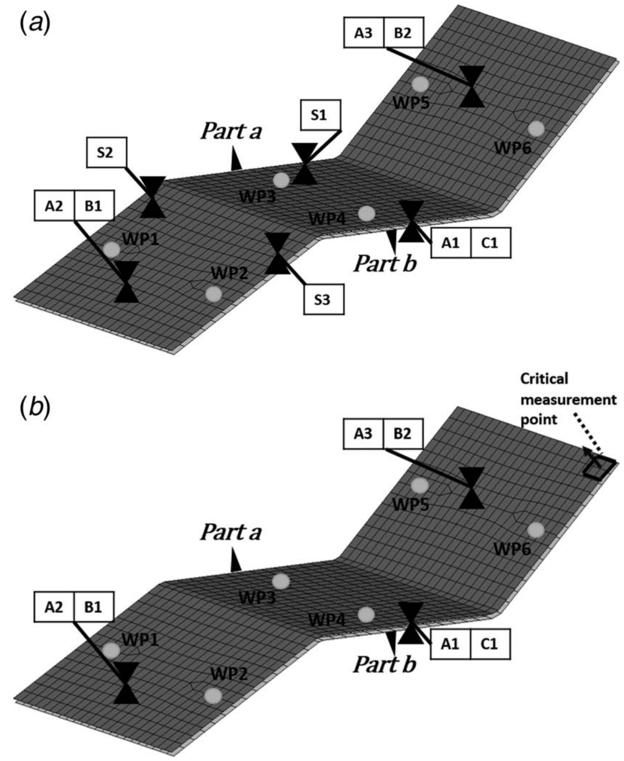

Fig. 4 Example of a two-sheet assembly with a critical point of measurement: (*a*) in assembly fixture and (*b*) in inspection fixture

To further clarify this point, consider the example in Fig. 4. There are six weld points on the assembly and a critical measurement point in the specified direction. The optimal sequence with respect to this measure is desired. In the initial step of the optimization, the sequences, [$\underline{1, 2}$, 3, 4, 5, 6], [$\underline{2, 1}$, 3, 4, 5, 6], [$\underline{3, 1}$, 2, 4, 5, 6], …, [$\underline{6, 1}$, 3, 4, 5, 2] are evaluated to include all the possible combinations of the first two sequence elements, and the relative displacements of each weld in Fig. 4(*a*), and the deformations in the critical measure in Fig. 4(*b*), for each sequence are retrieved. The function Φ is built to map the relative displacements, d, of WP_1 to WP_6, to the deformations of the critical measure in the inspection fixture. The next step of the optimization process is to evaluate all the possible combinations of the third element of the sequence. From this step, the function Φ is used to estimate the deformations in the inspection fixture, given the relative displacements of the weld points for different sequences. These sequences are [1, 2, $\underline{3}$, 4, 5, 6], [1, 2, $\underline{4}$, 3, 5, 6], [1, 2, $\underline{5}$, 4, 3, 6], and [1, 2, $\underline{6}$, 4, 5, 3]. This process is continued until the optimal sequence minimizing the Φ function is identified. Depending on the computation time window, two or three sequence elements can also be evaluated simultaneously in these steps. This sequence corresponds to the minimum deformations in the measurement point, in the specified direction, in the inspection fixture. With this approach, to identify the optimal sequence for a critical measure, only a small fraction of the complete simulations in the inspection fixture need to be performed, Sec. 2.3, and thereby, simulation time needed for optimization is reduced substantially.

3 Reference Assemblies

Two sheet metal assemblies are evaluated with the proposed approach, the correlation between the relative displacement of welds set in a sequence, and the assembly deformation measure is analyzed. The details of each assembly are provided in this section.

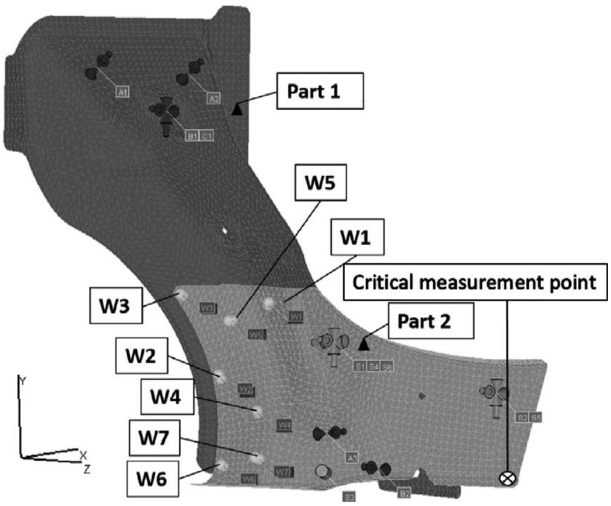

Fig. 5 Assembly A

3.1 Assembly A.

Assembly A is composed of two parts with seven weld points. The CAT model is prepared in the CAT-tool RD&T [32]. The three-dimensional scanned parts, in the deformed mesh form, are used as part deviation input. The positioning system, the weld points, and their corresponding numbering are shown in Fig. 5. The critical measurement point is also shown in the figure. The deformation in the X-direction is desired to be optimized in this measure. The sheet thickness for Part 1 is 1.6 mm and Part 2 is 1.2 mm. To evaluate the geometrical deformation of the assembly after springback, in the inspection fixture, with respect to a specific sequence, 7.28 s is required. Evaluating the relative displacements of the welds for each sequence in the assembly fixture requires 5.65 s. The evaluation times are calculated using a workstation with 2.7 GHz CPU and 32 GB RAM. The correlation analysis and optimization results are presented in Secs. 4.1.1 and 4.2.1.

3.2 Assembly B.

This assembly is composed of three parts with five weld points. The CAT model is prepared, and the contact modeling and the part deviation input are applied to the model, same as Assembly A. The CAT model of the assembly is presented in Fig. 6. The critical measurement point is shown in the figure, where the deformation in the X-direction needs to be optimized. The sheet thickness for Parts 1–3 are 0.8 mm. To evaluate the assembly's geometrical deviation in the inspection fixture, welded in a sequence, 7.63 s is required. Evaluating the relative displacements of the welds in the assembly fixture requires 5.27 s, using the same workstation as Assembly A.

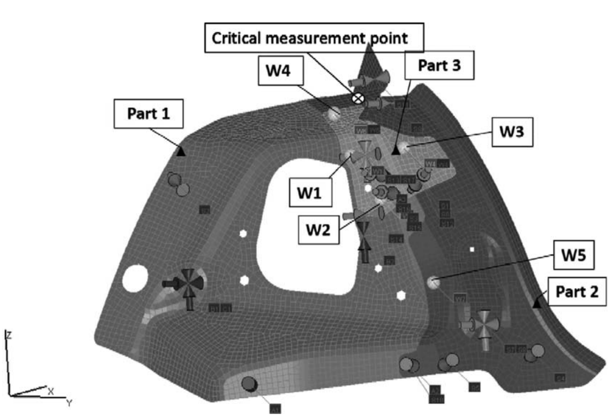

Fig. 6 Assembly B

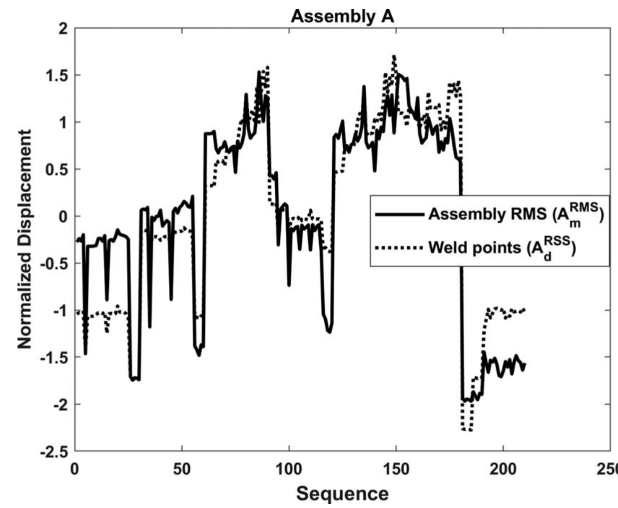

Fig. 7 Assembly A: comparison between A^{RSS_d} and A_m^{RMS}

Table 1 Overall assembly sequence optimization results

Assembly	Method	Optimal sequence	Assembly deformation (mm)	Optimization time (s)
A	A_m^{RMS}	[1,7,2,6,5,4,3]	0.4289	1594.3
A	A_d^{RSS}	[1,7,2,6,5,4,3]	0.4289	1237.3
B	A_m^{RMS}	[2,1,4,5,3]	1.0689	915.6
B	A_d^{RSS}	[2,1,4,5,3]	1.0689	632.4

4 Assembly Evaluation

The sequence optimization with respect to the relative displacements of the welds, A_d^{RSS}, and RMS of the deformations in all the assembly nodes, A_m^{RMS} are performed on both the reference assemblies and the retrieved sequence, and the optimization times are compared. The analyses of the critical measurement points are also performed. The detailed results for each assembly are presented in this section.

4.1 Overall Assembly Analysis.

For each assembly, the overall assembly, with respect to all the nodes of the assembly, are evaluated with the proposed approach of relative displacements analysis and compared with the complete simulation in the inspection fixture for both assemblies.

4.1.1 Assembly A. To compare the optimization objectives, the two measures A_d^{RSS} and A_m^{RMS} are normalized for all the combinations of the first three sequence elements. Figure 7 shows the behavior of the two measures among the sequences. The two measures follow the same trend. The proposed method and the corresponding measure A_d^{RSS} is capturing the sequence with the minimum deformation in the inspection fixture. To get an understanding of the correlation between the two measures, a correlation analysis is performed. Figure 8 shows the one by one linear correlation of the two measures. The ρ-value of 0.91 specifies a significant positive correlation between the two. The Spearman-ρ value of 0.9134 agrees with the results achieved from the Pearson coefficient above. The null-hypothesis test, when H_0 is no correlation between the two variables, results in the p-value is $3.2 \times e^{-81} \approxeq 0$. The H_0 is rejected, and the correlation exists with the significant level of correlation coefficients. The analysis is performed, while the sequence changes, and all the other parameters in the MIC and contact modeling are kept constant, and A_d^{RSS} and A_m^{RMS} are observed. Based on the results achieved, a significant correlation exists. Since all other parameters are kept constant, the weld relative displacements have

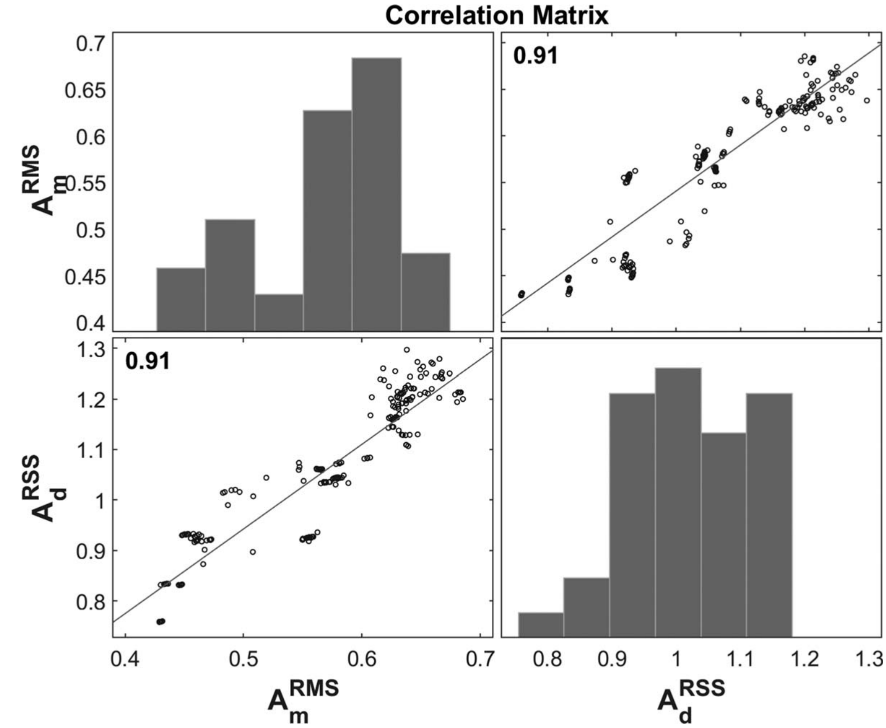

Fig. 8 Assembly A: correlation between A_d^{RSS} and A_m^{RMS}

caused the deformation behavior in the inspection fixture among the sequences.

Optimization of the sequences with respect to the measures is conducted using the stepwise algorithm, Sec. 2.4. The optimization results are reported in Table 1. Optimization with respect to the two objectives results in the identical sequences, with the assembly deformation (RMS) of 0.4289 mm. Considering the optimization time required in each method, the relative displacement of the welds as the objective, helps to save 22.39% of the optimization time, compared with the total assembly deformation RMS optimization.

4.1.2 Assembly B. The same analysis has been performed for this assembly. Since the assembly has five weld points, all the possible 120 sequences are evaluated, and the sequence that corresponds to the minimum assembly deformation is identified. Figure 9 shows the normalized RMS of the magnitude of displacements for all the nodes, in the assembly against the RSS of the relative weld displacements, for all the sequences. Both measures follow the same trend in this assembly as well. The correlation value ρ of 0.95 also indicates a significant positive correlation between the two measures, Fig. 10. With the same analysis as Assembly A, the Spearman-ρ of 0.81 agrees with the Pearson coefficient achieved. The p-value of the H_0 is $2.1 \times e^{-63} \approxeq 0$; therefore, the no-correlation hypothesis is rejected, and A_d^{RSS} causes the changes in A_m^{RMS}.

The sequence corresponding to the minimum assembly deformation is [2,1,4,5,3]. Considering the minimization of the proposed approach measure A_d^{RSS} results in an identical sequence as total assembly deviation minimization. The optimization time required to achieve the optimum sequence is 30.93% lower than optimization considering the RMS of the magnitude of the displacements for all the nodes. The summary of the results achieved for this assembly is presented in Table 1.

4.2 Critical Measurement Point Analysis. In addition to the overall assembly, the critical measurement points of the assemblies in the specified directions are evaluated. The summary of the proposed approach is as follows:

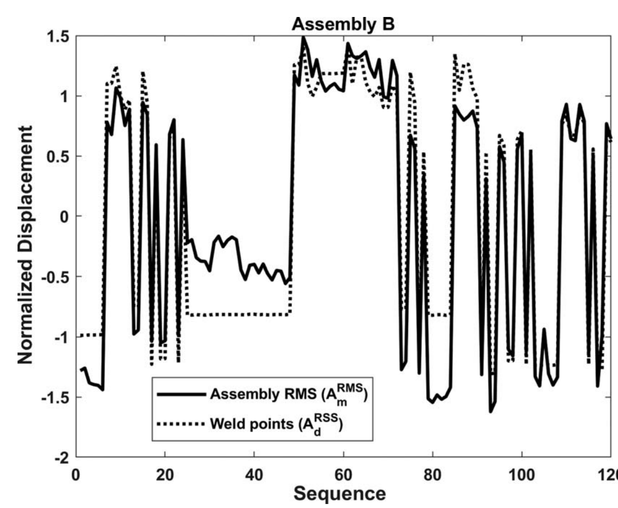

Fig. 9 Assembly B: comparison between A_d^{RSS} and A_m^{RMS}

(1) Perform the first step of the optimization, evaluating all the combinations of the initial elements, capturing the relative displacements of all the weld points, and the deformations in the inspection fixture.
(2) Build the SVM models mapping the weld relative displacements to the deformations in the inspection fixture for each sequence.
(3) Deploy the SVM models in the rest of the optimization steps to estimate the deformations in the inspection fixture, given the weld relative displacements for the specific sequences.

The details of the analysis of the critical measurement points for each assembly are provided below.

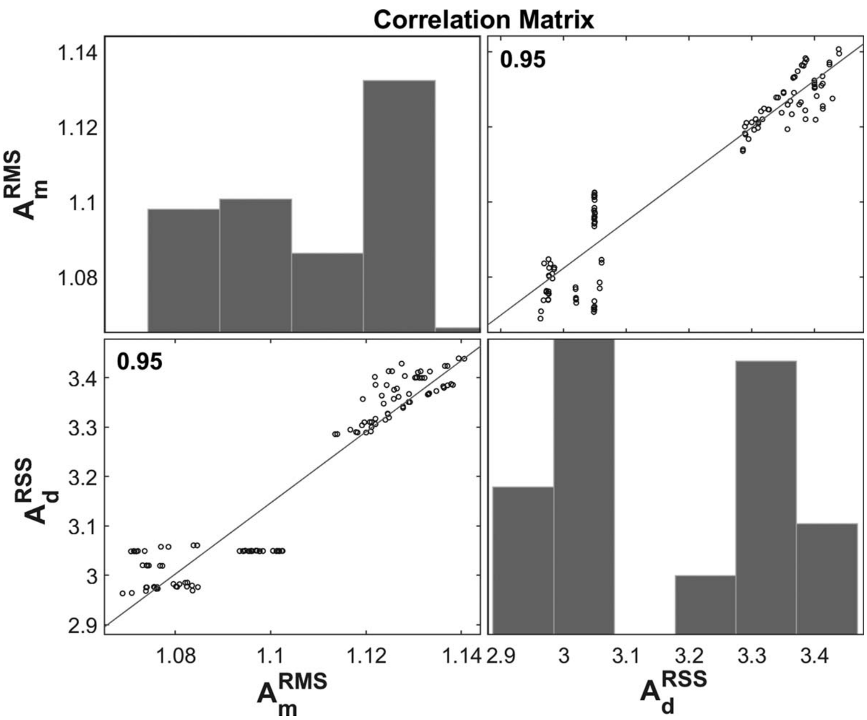

Fig. 10 Assembly B: correlation between A_d^{RSS} and A_m^{RMS}

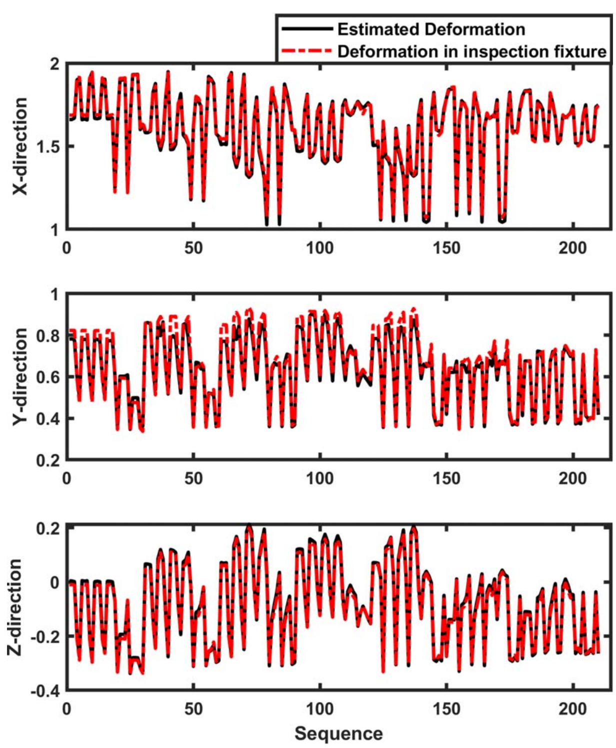

Fig. 11 Assembly A: estimated and simulated deformations in different directions in the critical weld point

4.2.1 Assembly A. This assembly consists of seven weld points, and there are in total 5040 possible sequences. The optimal sequence for the critical measurement point in the *X*-direction, minimizing the deformation, is analyzed. The first step of the optimization is performed, and all the combinations of the first two elements are evaluated (Sec. 2.5). This includes a total of 42 sequences. The SVM models, Φ_x, Φ_y, and Φ_z, are built using MATLAB for analyzing each direction in the measurement point. Figure 11 presents the simulated deformation in the inspection fixture, u, and the estimated value using the SVM models, $\hat{u}$, in each direction of the critical measurement point for 210 different sequences, including all the combinations of third to fifth sequence elements. The SVM models estimate the deformations in the inspection fixture, given the weld relative displacements with minimal errors. The sequence optimization for the critical measure in the *X*-direction is performed, and the results are presented in Table 2. The optimization using the SMV model of the weld relative displacements for sequence evaluation requires 13.2% less time, compared to the complete simulation in the inspection fixture, while the errors are marginal. With this approach, a lower number of complete simulations in the inspection fixture need to be performed, and thereby, optimization time will be lower, capturing only the weld relative displacements from the simulation.

4.2.2 Assembly B. This assembly consists of five weld points, with 120 different sequences. To optimize the sequence with respect to the deformations in the critical measurement point in the *X*-direction, all the combinations of the first two elements of the sequence are evaluated. This includes 20 sequences in total. Using the weld relative displacements in the assembly fixture and the deformations of the critical measurement point in the inspection fixture, the SVM models are built. Figure 12 shows the estimation of the deformations among all the possible sequences against the simulated value of the deformations in the inspection fixture. The SVM models follow the trend of the changes between the sequences and are able to identify the optimal space in all the directions. The optimization results for this assembly and the corresponding optimization time required are presented in Table 2. The sequence optimization results show that near optimal solutions with marginal errors can be achieved, using the weld relative displacements, while 23.19% less optimization time is required, compared to complete simulations in inspection fixture.

Table 2 Critical measurement point analysis

Assembly	Method	Optimal sequence	Assembly deformation (mm)	Error (mm)	Optimization time (s)
A	Simulated u	[1,7,5,2,6,3,4]	0.9903	–	742.6
A	Estimated $\hat{u}$	[1,7,5,3,6,2,4]	0.9938	0.0008	644.8
B	Simulated u	[5,2,4,3,1]	0.9212	–	610.4
B	Estimated $\hat{u}$	[5,2,4,1,3]	0.9213	0.0047	468.8

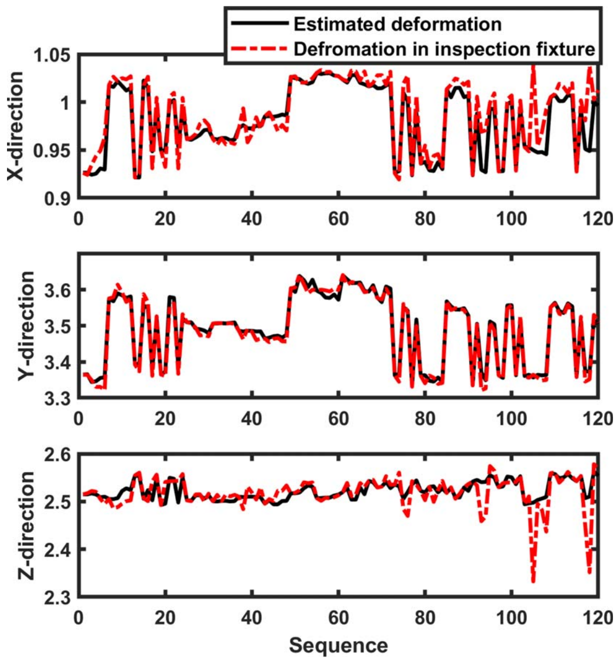

Fig. 12 Assembly B: Estimated and simulated deformations in different directions in the critical weld point

5 Conclusion

Spot welding sequence optimization is a combinatorial problem with an expensive to evaluate objective function. Considering part deviations, compliant variation simulation is performed to determine the geometrical outcome of the assembly with a specific welding sequence. This simulation method is based on deformation calculation in different steps. Springback calculation in the inspection fixture is one of the time-consuming steps of this simulation method. In this paper, an efficient spot welding sequence simulation in compliant variation simulation is introduced. The method is based on the calculation of relative displacements of the weld points in the assembly fixture. The method helps to bypass the springback calculation in the inspection fixtures for sequence optimization. The proposed approach has been applied to two sheet metal assemblies, and the sequence optimization is performed for the overall assembly and critical measurement points. Two approaches have been considered in the comparison of the retrieved results for the overall assembly.

(1) Sequence optimization with respect to the RMS of the magnitude of the displacements of all the nodes in the assembly in the inspection fixture, A_m^{RMS}.
(2) Sequence optimization with respect to the RSS of the relative displacements of the welds in the assembly fixture, A_d^{RSS}.

For the critical measurement points, a small fraction of the complete simulations in the inspection fixture are performed. SVM models are built to map the weld relative displacements in the assembly fixture to the deformations in the inspection fixture.

The results show that the proposed method, with the measure of relative displacements in the welds, has a significant positive correlation to the magnitude of the displacements in the assembly. The optimization results indicate that optimizing the welding sequence with respect to the relative displacements of the welds converges to the identical sequence to the magnitude of displacements in the inspection fixture. Furthermore, it has been shown that the total optimization time with the proposed method is improved by up to 30%. Additionally, with the proposed approach, sequence optimization of the critical measurement points requires only a fraction of the complete simulations in the inspection fixture, helping to reduce up to 23% of the optimization time. With the presented results, it is expected that using any other compliant variation simulation approach with FEM, i.e., DMC, the sequence of the applied joints, locking all the degrees-of-freedom in two nodes, can be evaluated with the presented method. The joining points relative displacements can be evaluated to estimate the assembly deformations concerning the joining sequences for more time-efficient simulations.

Future research includes expanding the proposed approach to evaluate other aspects in compliant variation simulation. The contact modeling step can be evaluated with the same approach, where the penetrations states are mapped to the final contact displacements for the different sequences. This step can potentially increase the model accuracy for final deformation evaluation.

Other assembly aspects, such as clamping order simulation can be studied with the proposed simulation approach. The approach can also be evaluated with respect to continuous welding applications, such as seam welding sequence analysis.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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