NordDesign 2010
August 25 – 27, 2010
Göteborg, Sweden

Variation Simulation of Spot Welding Sequence for Sheet Metal Assemblies

Kristina Wärmefjord, Rikard Söderberg and Lars Lindkvist
Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
kristina.warmefjord@chalmers.se

Abstract

One of many factors affecting the final geometrical outcome of a sheet metal assembly is the spot welding sequence, used when the parts are welded together. It is of course desirable to choose a welding sequence that minimizes both variation and deviation in critical dimensions of the final assembly. In this paper, the correlation between offset and standard deviation for different welding sequences is investigated. It turns out that in most cases, those two quantities are correlated, which of course facilitate the search of an optimal welding sequence. A method for including the welding sequence in variation simulation is also presented, as well as an investigation of the number of welding points needed to lock the geometry, i.e. the number of geometry points needed. The investigations are based on industrial case studies.

Keywords: spot weld, sequence, geometry points, variation simulation, tolerance, compliant, geometrical variation, geometry assurance

1 Introduction

In automotive industry, the body in white of a car consists of hundreds of sheet metal parts that are joined together. During this joining process, a lot of factors affect the final geometrical quality. It is important to have knowledge about the characteristics of as many as possible of those factors, not only to be able to reduce their effect, but also to be able to include those factors in variation simulations. Variation simulations are crucial tools in early stages of the product development process in automotive industry and are used to predict the outcome in critical dimensions [1], [2]. Since the demands on sustainability is increasing, virtual tools become even more important in the future, since they can reduce the need of tests and pre-series.

In the simulations it is necessary to include factors such as design concept, part variation, locating schemes, joining method et cetera. In this paper, a closer study of joining through spot welding is conducted. How to include spot welding sequence in variation simulations and also its effect on as well variation as on mean value in critical dimensions is investigated.

The effect of spot welding sequence is investigated by for example Liu and Hu [3], but they do not include the phenomenon in variation simulations. Lee *et al*. [4] are examining how welding sequence for continuous welding can be included in variation simulation by using a pre-generated database. Wärmefjord *et al*. [5] include welding sequence in variation simulations and verify the result on an industrial case study. They also investigate different strategies for finding an optimal welding sequence with respect to geometrical variation.

Hu *et al*. [6] investigate the effect of welding sequence on a dash panel assembly. They propose a numerical simulation method for compliant assemblies, including the possibility to simulate different welding sequences, and verify their results using experimental data.

Shiu *et al.* [7] investigate the relationship between stress build-up due to different spot welding sequences and the resulting dimensional variation. General guidelines for welding sequences are also established. Liao [8] describes how to find the optimal number and position of the spot welds using a genetic algorithm for minimizing an objective function, which is the weighted sum of the deviations and/or variations in the inspection points. Xie and Hsieh [9] are also using a genetic algorithm to find spot welding sequences that minimize deformation in user-defined points. They also take cycle time into consideration. The algorithm is implemented in the software EAVS (Elastic Assembly Variation Simulation). This work considers however only deformation, not variation.

Liu and Hu [10] present two principles for minimizing the dimensional variance, namely to weld from weak to strong and to weld simultaneously if possible.

Yang and Shao [11] divide the welding points into two groups, where one of the groups contains points with large influence on the welding distortion. The distortion considered is only due to influence of heat. To the group of points with large influence on distortion belong the welding points located in the middle of the parts.

1.1. Scope of the paper

The correlation between deviation and variation for different welding sequences is investigated. How the level of variation and deviation change with the number of executed welding points in a predetermined welding sequence is also studied. This is used to determine the number of "geometry points", i.e. the number of points used to lock the geometry.

In Section 2 an overview of the spot welding procedure in automotive industry is given. It is followed by a description of how the spot welding sequence can be included in variation simulations in Section 3. The method is verified using an industrial case study. In Section 4 the correlation between offset and variation for different welding sequences is investigated for a number of case studies. A stepwise evolution of how the level of variation and the offset change with the number of executed welding points, used to determine the number of geometry points needed, is conducted in Section 5. Finally, the conclusions are found in Section 6.

2 Spot welding in automotive industry

In this section, some concepts regarding welding procedures in automotive industry is introduced.

To produce a car, a large number of sheet metal parts are joined together to subassemblies, which constitute the body in white. The parts are usually joined using different kind of welding methods, such as laser welding, spot welding, MIG welding and so on. In this paper, spot welding is considered. During the welding process of as well spot welding as other welding alternatives, heat is generated. This may lead to deformations of the parts. For spot welding, this deformation is though of minor importance [12] and is not included in this work.

A spot welding gun has two electrodes, which are applied from either side of the sheet metal parts. When the parts are in contact, an electric current is applied and the result is a small spot, heated to the melting point, in which the parts are joined. The welding gun is usually a balanced gun or a position gun. For both types of guns, the electrodes are applied simultaneously from each side of the metal sheets in order to connect the parts. With a balanced gun, equal forces are applied to the welding pins. Therefore, the sheet metal parts will meet in a position of equilibrium. When a position gun is used, the welding pins will meet each other in a fixed position, no matter what the position or stiffness of the sheet metal parts are. Therefore, even if the parts are deflected, they will still be forced to move to that fixed position when the welding gun is applied. The different kinds of welding guns give different result and the type of welding gun must consequently be specified. In this paper balanced guns were used.

2.1. Geometry points and respot points

When it comes to welding order, the normal procedure is to weld the so called geometry points first. These welding points lock the geometry and after the geometry points are welded the assembly can be released from its fixtures and the remaining points, the so called respot points, can be welded in one of the following stations without any obvious effects on the geometry. However, different welding orders for the geometry points give rise to different forces and therefore also to different displacements in the final assembly. For the respot points the welding sequence should be chosen mainly with respect to cycle time.

3 Welding sequence in variation simulations

The welding sequence has a well-known effect on the geometrical variation and deviation in the final assembly. Therefore it is also very important to include this effect in variation simulations. A method to do this is described in Section 3.1. An industrial case study is used to show how the agreement between the simulated result and the actual outcome is further improved by the use of the suggested method for including welding sequence in variation simulations. This material is also included in [5].

3.1. Simulation of spot welding sequence

In compliant (non-rigid) analysis, parts are allowed to bend or deform during positioning, which allows for over-constrained locating systems. When assembling the parts, they are positioned in fixtures in the assembly stations and clamped, which may cause deformations of non-nominal parts. Then they are joined together and finally, the subassembly is released and is allowed to springback. During virtual assembly, there is a risk that the parts cut through each other. To avoid that, not very realistic behavior, contact modeling is utilized. A method for including contact modeling in variation simulations is described in [13].

If the parts and fixtures are nominal and there is no gap to be closed between the parts, then the welding sequence will not affect the geometrical outcome.

To be able to handle deformations and springback, part stiffness and clamping forces must be included in order to predict robustness and variation in compliant analyses. To capture the non-rigid behavior of the parts and assemblies it is necessary to include the finite element method in the variation simulations. The procedure of doing that for a single station assembly is explained in several papers, see for example [2] or [14]. In this paper, welding sequence is also included, see step 2 below. The procedure to calculate the final result of a complete single station assembly can be summarized in the following steps. Those steps can of course be accomplished for an arbitrary number of parts, analogous with the procedure for two parts, described here.

Step 1: Clamping the parts in the fixture.

The parts A and B are positioned in their fixtures and over-constrained locating systems are applied. The gaps to be closed in the clamping points are gathered in the vectors $\{\mathbf{u}_\mathbf{p}^\mathbf{A}\}$

respectively $\{\mathbf{u_p^B}\}$**.** To close the gaps, forces $\{\mathbf{F_p^A}\}$ respectively $\{\mathbf{F_p^B}\}$ are applied. The part stiffness matrices are denoted $[\mathbf{K_p^A}]$ respectively $[\mathbf{K_p^B}]$**.** Then the following relations hold:

$$\{\mathbf{F_p^A}\} = [\mathbf{K_p^A}]\{\mathbf{u_p^A}\} \tag{1}$$

$$\{\mathbf{F_p^B}\} = [\mathbf{K_p^B}]\{\mathbf{u_p^B}\} \tag{2}$$

<u>Step 2</u>: Welding the parts together, welding point i=1,...,N

To set welding point *i*, a force $\{\mathbf{F_a^i}\}$, where the index ***a*** stands for assembly, is applied and the following relation holds:

$$\{\mathbf{F_a^i}\} = [\mathbf{K_a^{i-1}}]\{\mathbf{u_a^{i-1}}\} \tag{3}$$

After welding point *i* is set, the assembly is released from its fixture and will then springback. The stiffness matrix $[\mathbf{K_a^i}]$, used to calculate the springback, describe the stiffness of the assembly after welding point *i* is set.

After springback, the assembly is brought back to its position by applying the clamps again and the required force $\{\mathbf{F_a^i}\}$, including as well clamping forces as forces due to contact modeling, to do this is registered.

The stiffness matrix $[\mathbf{K_a^i}]$ is updated for every new welding point by adding a new matrix $[\mathbf{K^i_{wp(iA,iB)}}]$, locking three translations and three rotations corresponding to the added welding point, to the stiffness matrix from the previous step. This means that

$$[\mathbf{K_a}^{\mathbf{i}}] = [\mathbf{K_a}^{\mathbf{i-1}}] + [\mathbf{K_{wp(iA,iB)}}] \tag{4}$$

For the very first welding point, the matrix $[\mathbf{K_a^0}]$ refers to the original part stiffness matrices, i.e. one for each part. The deviation used in the first welding step, $\{\mathbf{u_a^0}\}$, corresponds to the part deviations.

Since the force and the stiffness in each step is known, the deviation from nominal after adding welding point *i*, $\{\mathbf{u_a^i}\}$, can be calculated.

<u>Step 3</u>: Springback (Removing fixture and clamps)

When all welding points are set and the assembly is unclamped it will springback. To simulate the springback, a force $\{\mathbf{F_a}\}$ corresponding to the force $\{\mathbf{F_a^N}\}$, but in the opposite direction, is applied. Using the relation

$$\{\mathbf{F_a}\} = [\mathbf{K_a^N}]\{\mathbf{u_a}\} \tag{5}$$

the final assembly deviation $\{\mathbf{u_a}\}$ can be calculated:

$$\{\mathbf{u_a}\} = [\mathbf{K_a^N}]^{-1}\{\mathbf{F_a}\} \tag{6}$$

3.2. Applying the simulation method on an industrial case study

The method suggested in the previous section is implemented in the variation simulation software RD&T [15] and in order to test the method it is applied to an industrial case study. This A-pillar assembly consists of two parts, the A-pillar itself and its extension. The parts are assembled using nine spot welds, shown in Figure 1. This subassembly was originally picked out for analysis, since there have been a lot of difficulties associated to it. The level of variation in the subassembly has been unacceptably high and the behavior of particularly the extension has been hard to predict.

The simulations are based on inspection data on part level, i.e. measurements before welding. The simulation results are compared to inspection data on assembly level, i.e. measurements after the parts were welded together. In the simulation of mean value deviation, scan data from one single component was used. Both parts were scanned before assemblying the parts and this information was used as input to the simulations. The simulated result was then compared to scanning data from the complete assembly. For the simulations of variation, inspection data from a number of components were used.

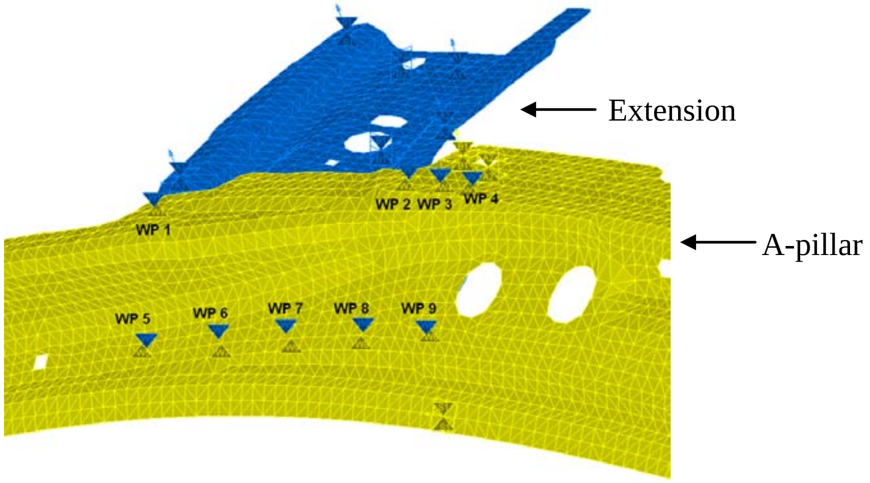

Figure 1: The nine welding points, A-pillar assembly

The simulations are performed with and without respect to welding sequence. When welding sequence is not included, the spot welds are executed simultaneously. For mean value predictions, the results are shown in Figure 2 and for prediction of 6*s* the results can be seen in Figure 3. The graphs show comparisons between inspection data of the final subassembly and the predicted values for a number of inspection points. As can be seen in the figures, the correspondence between inspection data and simulation data improves when welding sequence is included. A way of quantifying this improvement is to look at the mean value of the absolute deviation between inspection data and simulation data.

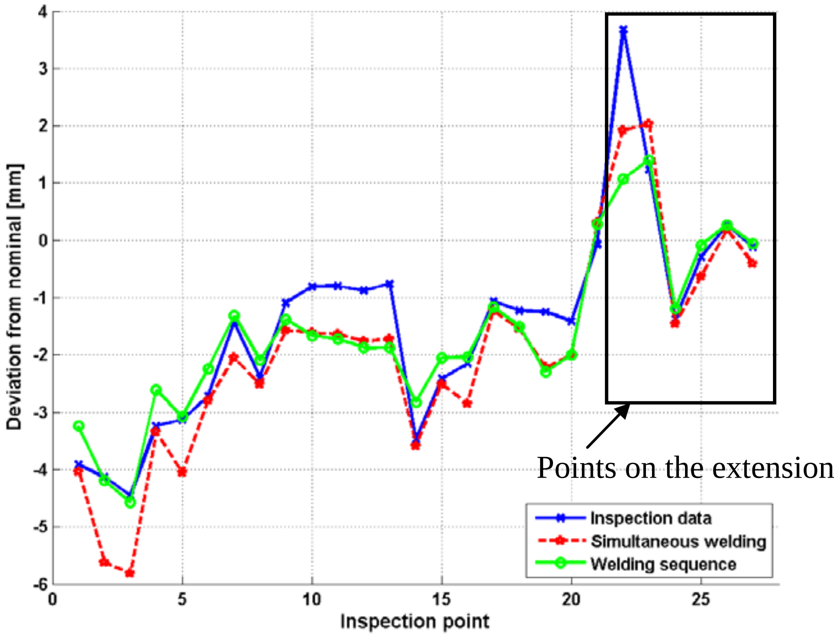

Figure 2: Comparison of mean value for inspection data and simulation data.

Since the points on the extension are the ones most sensitive to welding sequence and also the ones that are most difficult to predict, the calculations are based on those points. For the mean value prediction the deviation is 0.54 for simultaneous welding and 0.51 for welding in sequence. The corresponding figures for prediction of 6s are 2.85 and 2.58.

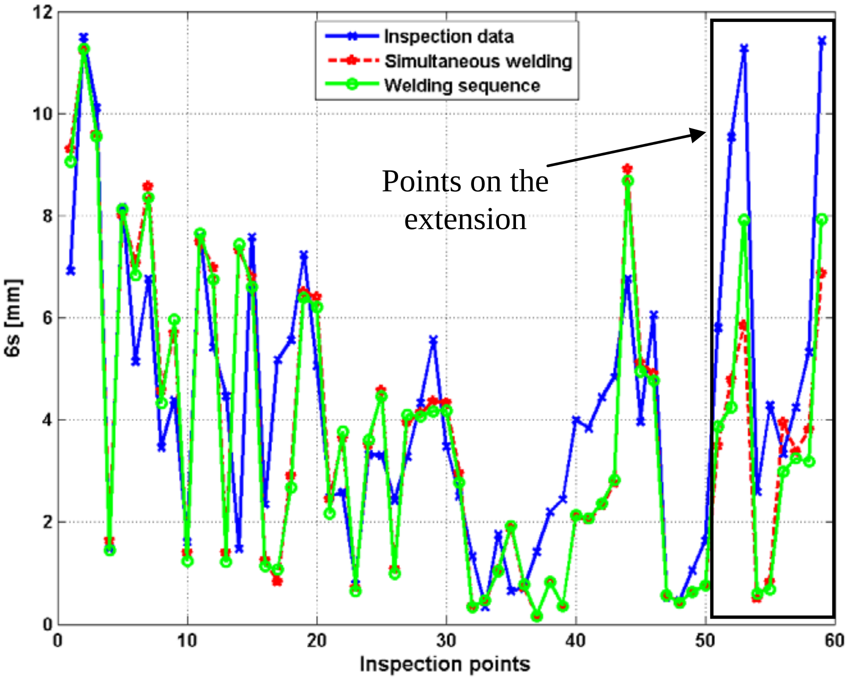

Figure 3: Comparison of 6s for inspection data and simulation data.

4 Correlation between deviation and variation for different welding sequences

In this section the correlation between deviation and variation for all possible welding sequences is studied using a number of industrial case studies. The case studies considered are shown in Figure 4.

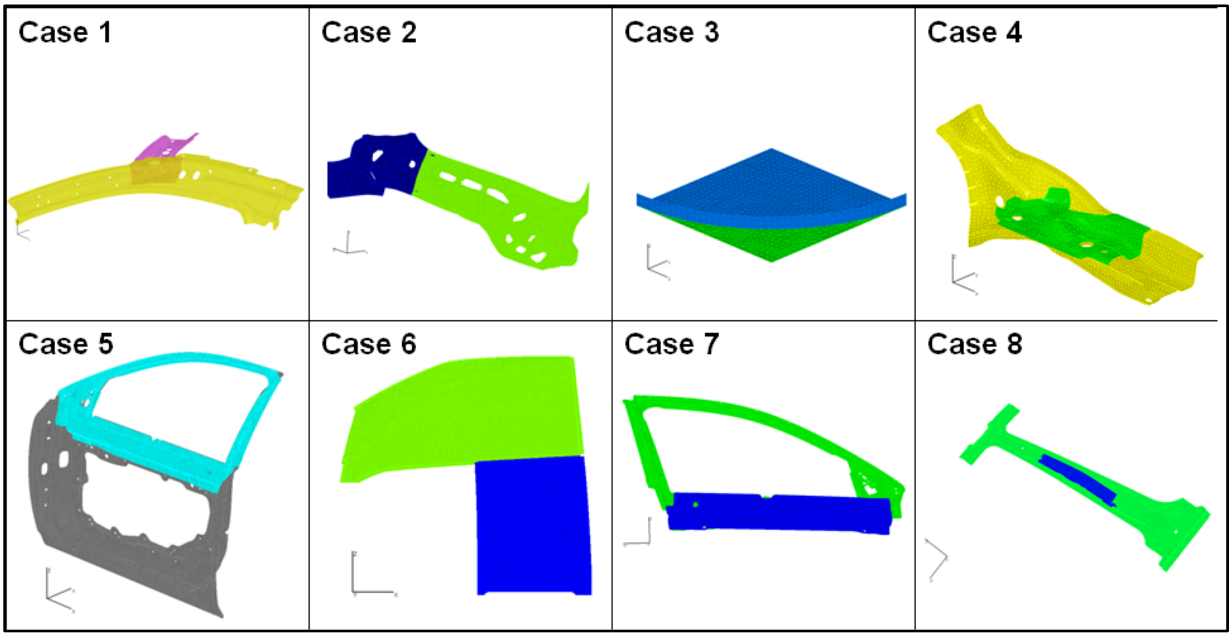

Figure 4: Eight different case studies.

All but one case are industrial case studies from automotive industry, although the number of welding points are reduced to four welding points. In [5], those cases were investigated in order to investigate different strategies to find the optimal welding sequence with respect to variation. In Table 1 the correlation between the root mean square (RMS) values for offset from nominal and for standard deviation is shown for all cases. Since four welding points are used in each case, there are $4! = 24$ different possible welding sequences. The correlation calculations are based on those 24 different simulations. The differences between the best and the worst sequence are also shown. As can be seen, both the offset and variation can in most cases be considerably improved by choosing a good welding sequence.

Table 1: Correlations between offset and standard deviation for different welding sequences.

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Correlation	0.63	0.79	1.00	0.98	0.98	0.09	1.00	0.85
Difference best/worst sequence, RMS offset	48%	24%	39%	9%	3%	18%	36%	11%
Difference, best/worst sequence, RMS std	34%	28%	38%	8%	3%	41%	27%	13%

Case 1, 5 and 6 are also tested with a larger number of welding points. For case 1, all the nine industrial welding points are used and a sample from all possible sequences is used in the simulations. A total of 73 different sequences were tested. Inspection data from measurements on part level were used as input tolerances in the simulations. This resulted in a correlation of 0.55 between offset and standard deviation for the different sequences. The difference between the best and worst of the tested sequence was 68 % for RMS of offset and 59 % for RMS of standard deviation.

For case 5, ten welding points were used and 191 different welding sequences were tested. This resulted in a correlation of 1.00 and the difference between the best and worst of the tested sequences was 86 % for RMS of offset and 77 % for RMS of standard deviation.

For case 6, nine welding points were used and 73 different sequences were tested. A correlation of 0.30 between offset and standard deviation for the different sequences was registered. The difference between the best and worst of the tested sequence was 363 % for RMS of offset and 183 % for RMS of standard deviation.

The correlations are quite strong in all cases but case 6, where there is almost no correlation at all. When more welding points are used, the value of the correlation for case 6 increases, but it is still a weak correlation. A strong correlation between offset and variation is of course a great advantage when it comes to finding a good sequence with respect to the geometrical outcome of the final assembly. Then there is no need to compromise between a sequence suitable to reduce offset and a sequence suitable to reduce variation, instead both requirements can be more or less fulfilled.

For case 6, which shows almost no correlation between RMS for mean value and RMS for standard deviation, it can though be noted that the sequence that is best with respect to variation is also one of the best with respect to mean value; it is only 2 % poorer then the best one for mean value. That kind of behavior can also be observed when nine welding points are used. This is important, since a high correlation value indicates that a good sequence for standard deviation is also a good sequence for mean value, but also that the opposite is true. In this case, only the good sequences are of interest.

It should though be noted that the correlation between offset and variation probably is dependent on the chosen cases and their tolerances. For all cases presented in Table 1, a small variation tolerance is applied to all positioning points and larger tolerances, containing both offset and variation, are applied to welding points and to contact points.

The general applicability of those results can be strengthen further by looking at a linearized model connecting movements, $\boldsymbol{\delta}$**,** in positioning points and the resulting movements, $\boldsymbol{x}$**,** in the inspection points. Such a model can be described as [16]:

$$\boldsymbol{x} = \boldsymbol{A\partial} + \boldsymbol{z} \tag{7}$$

where $\boldsymbol{z} \sim N(0, \sigma^2 I_p)$ is Gaussian noise modeling other sources of variation. Using this model, the relation between the variations in inspection points and the variations in locators can be expressed as

$$\boldsymbol{\Sigma_x = A\Sigma_\partial A^T + \sigma^2 I} \tag{8}$$

and the relation between offset in the inspection points and the offset in the locators as

$$\boldsymbol{\mu_x = A\mu_\delta} \tag{9}$$

This model is not complete. Part variations in contact points are not taken into account. But still, the model describes one important component of the total movements in the inspection points. As seen are both the mean value and the variation in the inspection points affected by the matrix $\boldsymbol{A}$. One factor controlling the magnitude of $\boldsymbol{A}$ is the welding sequence, why it is not very surprising to find the rather strong correlations between offset and standard deviation for the different welding sequences.

5 Geometry welding points

As described in Section 2, welding points are usually divided into geometry points and respot points. In automotive industry it is often argued that it is necessary to use a minimum of four geometry welding points to lock the geometry for assemblies substantially smaller than the ones considered in this paper. To explore how the offset from nominal and the variation levels change with the number of executed welding points, the behavior for the eight cases are investigated.

It is of course of great interest to minimize both the variation and the offset from nominal in the final assembly, and as seen in the previous section those two are often correlated. To combine the values of variation and offset, the idea of inertial tolerancing is utilized.

Inertial tolerancing is a way of combining specifications on both offset and variation in the same notation [17]. The inertia in inspection point j is defined as

$$I_j = \sigma_j^2 + \left(\mu_j - target_j\right)^2 = \sigma_j^2 + \delta_j^2, \tag{10}$$

where σ^2 is the variation and δ is the difference between the mean value μ and the target value. Here, the target equals 0. For the case studies presented in this section, where the mean deviation and the variation is determined for all nodes in the mesh, the total inertial root mean square sum is calculated as

$$RMS_I = \sqrt{\frac{1}{p}\sum_{j=1}^{p} s_j^2} + \sqrt{\frac{1}{p}\sum_{j=1}^{p} \bar{x}_j^2}, \tag{11}$$

where s^2 and $\bar{x}$ are estimates of σ^2 and μ and p is the number of nodes in the mesh.

The RMS_I is calculated for k=1,2,3,4 executed welding points for all case studies, and also for some extra welding points for case 1, 5 and 6. The results are shown in Figure 5. The sequence chosen for each case, except for case 5 with nine welding points, is the one that minimizes RMS_I when all welding points are executed. For case 5 with nine welding points, the sequence used in industrial production is utilized. A detailed study of the optimal welding sequences with respect to minimized variation can be found in [5].

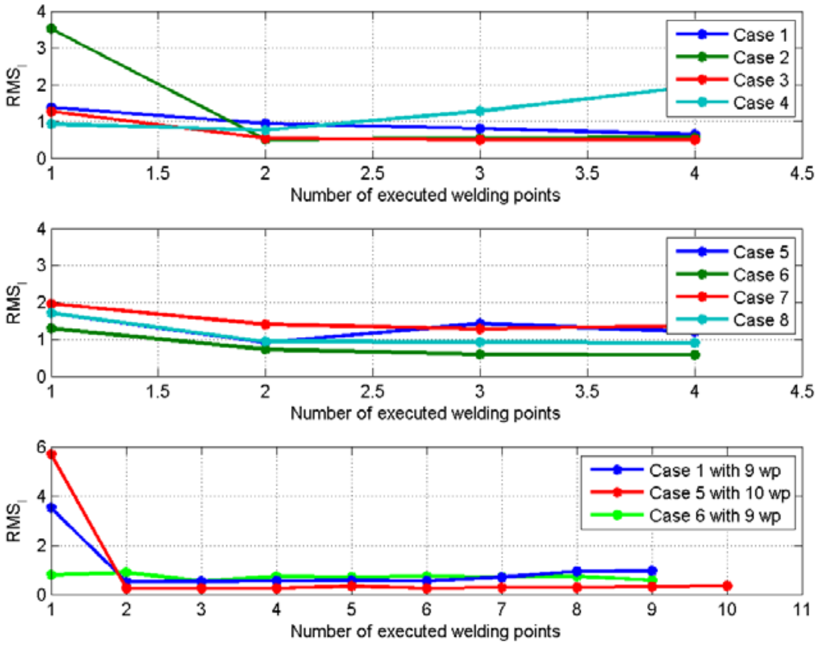

Figure 5: Values of RMS$_I$ for an increasing number of executed welding points.

As can be seen in the figure, the RMS_I value decreases considerably when the second welding point is added. But thereafter, the value levels away. For some cases it decrease a little more after the second welding point is executed, and for some other cases the RMS_I value even increase a little bit when additional welding points are added. But the main conclusion is that after the second welding point is executed, the geometry of the assembly does not change very much. Therefore, it would from a geometrical perspective, usually be enough with two geometry points.

Those results should possibly be usable when it comes to find an optimal welding sequence as well. If only the k first welding points in a sequence are of interest, instead of all N welding points, the number of different possible sequences decreases from $N!$ to $N!/(N-k)!$. It is however necessary to investigate if this behavior is valid for all sequences, not only for the good ones tested here.

6 Conclusions

In this paper two aspects of spot welding sequence have been examined from a geometrical point of view. The investigations are based on industrial case studies, although the number of welding points in some cases is reduced. All case studies consist of two parts. First, the correlation between offset from nominal and variation for different welding sequences was investigated. It turned out that there was an unambiguous correlation between the two quantities in all cases but one. For this case, the best sequence for variation was however good also for the offset. From those case studies, the conclusion is that there is no contradiction between a sequence suitable to suppress variation in the final assembly and sequence suitable to suppress the offset.

Further, the number of necessary geometry points was investigated. The geometry points are spot welding points intended to lock the geometry. After the geometry points are welded, the assembly can be released from its fixtures and the remaining points, the so called respot points, can be welded in one of the following stations. The investigations of the case studies showed that after two welding points were executed, the geometry was quite stable, so based on a geometrical point of view, two geometry points would be enough to use when assembling two parts.

By improving the quality of variation simulations, i.e. the conformity between actual and simulated results, the risk of misjudgements can be reduced and thereby can also the scrap rate be reduced. That will benefit sustainability, with respect to both economical and ecological aspects. Also the social sustainability is gained by an increased use of virtual tools, since this usually implies improved working conditions.

Acknowledgement

This work has been part of the Wingquist Laboratory VINN Excellence Centre research program. In the centre Chalmers University of Technology and Swedish industry conduct collaborative research funded by The Swedish Governmental Agency for Innovation Systems (VINNOVA). The support from the centre is gratefully acknowledged.

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