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# Welding of non-nominal geometries – physical tests

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## Abstract

The geometrical quality of a welded assembly is to some extent depending part positions before welding. Here, a design of experiment is set up in order to investigate this relation using physical tests in a controlled environment. Based on the experimental results it can be concluded that the influence of part position before welding is significant for geometrical deviation after welding. Furthermore, a working procedure for a completely virtual geometry assurance process for welded assemblies is outlined. In this process, part variations, assembly fixture variations and welding induced variations are important inputs when predicting the capability of the final assembly.

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*Keywords:* Welding; deviation; fixturing; clamping

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## 1. Introduction

In aerospace industry, sustainability requirements are drivers of lightweight solutions. As a result of this, large casted parts are being replaced with smaller parts in lighter material that are welded together. This strategy is sometimes referred to as "fabrication". Weight is saved, but other problems related to tolerances and geometrical variation arise. The parts themselves are non-nominal due to previous manufacturing processes and the assembly fixtures might also vary due to wear. Furthermore, the welding process itself adds variation. Those sources of variation might lead to products not fulfilling customer requirements or costly and time consuming rework operations.

To compensate for fixture or part disturbances, the parts to be welded are often clamped to nominal position close to the weld path. However, this introduces stresses in the parts and the effects from this are not fully understood. In this work, the effect from clamping is investigated using physical tests. The focus is on geometrical deviations after welding, so effects from the introduced stress on life, strength etc are not considered.

Earlier, this kind of investigations have been done based on simulations [1, 2]. However, no physical verifications were done. Furthermore, in this paper the effects from symmetry in part disturbances are investigated.

In Section 2, an overview of geometry assurance is given. In Section 3 the case study is presented, followed by the results from the case study in Section 4. In Section 5, some guidelines for geometry assurance of welded assemblies are presented. Conclusions can be found in Section 6.

## 2. Geometry assurance

Geometry assurance is a concept used to gather activities and tools used to minimize the effect of geometrical variation in parts and in the assembly process with respect to geometrical quality of the final product. Low geometrical quality of the final product means large geometrical variation of the product, often leading to severe effects on both functional and esthetical requirements. Geometry assurance is a natural part of the product development cycle in automotive industry, but is in many cases not completely adapted within aerospace industry. With larger series, fabrication strategy and

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increased competition, a process for geometry assurance is sought after also in aerospace industry.

The geometry assurance process starts with finding robust design concepts, insensitive to variation. Different concepts can be compared and evaluated. Locating schemes, which describe how the parts are positioned during assembly, control the variation propagation from part level to assembly level and are critical during this stage of the geometry assurance process. A rigid part has six degrees of freedom (three rotations and three translations) that must be locked by the locating scheme. For a non-rigid part, additional support points can be added to the original six locating points to avoid deformation of the part due to gravity and other forces. The locating points are physically realized by the contact between the fixture and the part, i.e. the locators. More about locating schemes can be found in [3].

Geometry assurance activities are also present in the verification phase, where the product and the production system are physically tested and verified. In this phase also inspection preparation and off-line programming of coordinate measurement machines and scanning equipment takes place. Here, all inspection strategies and inspection routines are decided.

In the production phase all production process adjustments are completed and the product is in full production. Focus in this phase is on inspection data to control production and to detect and correct increased deviation and/or variation [4]. There is a cost for inspection, but this cost should be compared to the cost for non-detected quality issues [5].

Among the tools in the geometry assurance toolbox, variation simulation is perhaps the most important one. This kind of simulation takes part variation, assembly fixture variation and assembly process variation into account and predicts the geometrical outcome of the final assembly. By using such a tool iteratively, tolerances can be chosen in such a way that the requirements on assembly level are fulfilled.

A lot of work has been done in the area of variation simulation for non-rigid sheet metal parts, joined by spot welding or riveting [6-9]. For spot welding, the effect from heat is assumed to be minor and not included in the simulation. Often, variation simulation is based on the Monte Carlo (MC) method, where thousands of iterations are run in order to create statistical distributions for the deviation in a number of critical dimensions on the final assembly. In order to reduce the simulation time for non-rigid variation simulation, the method of influence of coefficient (MIC) is used [10]. The MIC means that a linear relationship between part deviations and assembly spring-back deviations is used in the simulations to avoid new finite element analysis (FEA) calculations in each MC iteration.

Considering assemblies joined by continuous welding, not that much work has been done in the area of variation simulation. The welding process give rise to heat that deforms the parts, changes in the mechanical properties and the micro structure and may also introduce, or release, residual stresses.

Deformation due to welding is difficult to include in variation simulation in an efficient way, since the simulation of the welding process normally is very time consuming and not possible to linearize, so the MIC method cannot be applied. Welding simulations are therefore usually done on nominal models.

However, in [1] variation simulation and welding simulation were combined and it was shown that it is not possible to do a variation simulation and a welding simulation separately and superpose the results. The effect from welding must be calculated for each MC iteration.

Lee et al. [11] used a pre-genereated database to include the effects from welding. They did however not consider the coupling between part variation and welding distortion. Lorin et al. [12, 13] have developed a fast and somewhat simplified welding simulation method that can be combined with variation simulation. Madrid et al. [14] present a conceptual framework for variation contributors to fabricated aerospace components.

## 3. Case description

The purpose of the case study is to investigate:

- If deviations on part level affect the deviation after welding on subassembly level.
- If yes, what this relation looks like.

The case study is consisting of two rectangular parts that are to be welded together, as seen in the sketch in Fig 1 and the photo in Fig 2. A locating scheme with one additional support point is used. The locators A1, A2, A3 and S1 control the part in Y-direction (in/out of the plane) and are physically realized with clamps (marked with X in Fig 1). The locators B1 and B2 control the part in X-direction and the locator C1 in Z-direction. B1/C is physically realized with a pin in the fixture and a round hole in the part (round circle in Fig 1) while B2 is physically realized with a pin/slot contact (oval hole in Fig 1).

The positions of locators A2 for plate 1 and/or plate 2 are disturbed according to the test plan seen in Table 1. Note that some test cases were identical (test 1-3, 8-9 and 11-12 respectively). Those groups are colored grey in Table 1. At this stage, only disturbances in Y-direction were investigated. In future research, different kind of disturbances and combinations thereof might be of interest to analyze.

The variation in the part geometry, i.e. the difference between the different plates used in the experiment, was kept to a minimum by laser cutting the parts.

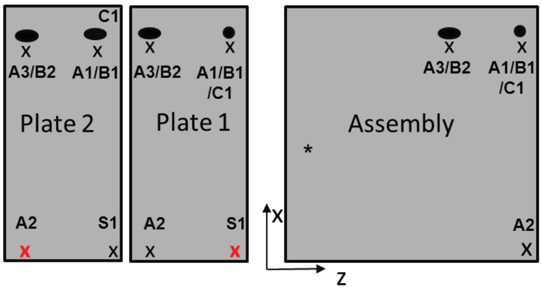

Fig 1: A sketch of the case study.

The plates are clamped to nominal position in support points S1 on both plates before welding, meaning that the plates are very close to nominal in the weld line. Due to the disturbance in locators A2, some stress is however introduced in the plates during clamping.

After this the plates are welded together and the deviation after welding in the point marked with a * in Fig 1 is registered. Before inspection, the welded assembly is allowed to cool down and all locators/clamps but the one indicated in the right part of Fig 1 is removed/released. This allow the assembly to springback, and the deviation after welding can be obtained.

The material of the plates is Inconel718 in annealed condition. The plate thickness is 2.54 mm and welding parameters can be found in Table 2. The high current is incrementally active for 0.3 s and the low current 0.2 s.

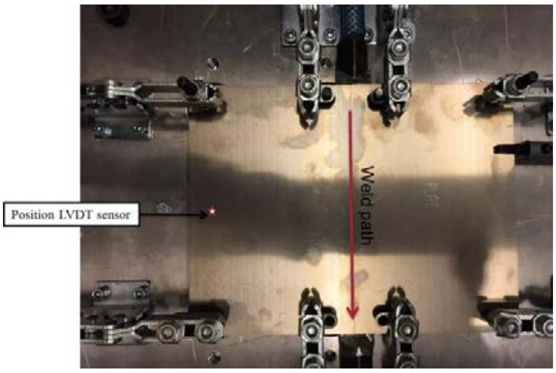

Fig 2: The case study.

Table 1: Disturbances.

| Test | Plate 2 Disturbance A2 (mm) | Plate 1 Disturbance A2 (mm) |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 0 | 0 |
| 3 | 0 | 0 |
| 4 | 0.1 | 0 |
| 5 | 0.5 | 0 |
| 6 | 1.0 | 0 |
| 7 | 1.5 | 0 |
| 8 | 2.0 | 0 |
| 9 | 2.0 | 0 |
| 10 | 0.1 | 0.1 |
| 11 | 0.5 | 0.5 |
| 12 | 0.5 | 0.5 |
| 13 | 1.0 | 1.0 |
| 14 | 1.5 | 1.5 |
| 15 | 2.0 | 2.0 |
| 16 | 0.1 | -0.1 |
| 17 | 0.5 | -0.5 |
| 18 | 1.0 | -1.0 |
| 19 | 1.5 | -1.5 |
| 20 | 2.0 | -2.0 |

Table 2: Welding parameters, TIG welding.

| Voltage, high (V) | Voltage, low (V) | Current, high (A) | Current, low (A) | Welding speed (mm/s) |
|---|---|---|---|---|
| 12 | 9 | 65 | 115 | 2.5 |

## 4. Results

The resulting inspection data from the case study described in previous section can be seen in Fig 3. The blue and the red bars show disturbances introduced in the locators A2 for plate 1 and plate 2. The red line shows the resulting deformation of the welded assembly in the point marked with a * in Fig 1 and Fig 2. As already mentioned, the introduced disturbances in each one of the test groups 1-3, 8-9 and 11-12 respectively are equal, leading to 16 different test setups. The inspection values for each of the groups with identical setups are encircled in Fig 3. It can be noted that despite equal disturbance in the above mentioned groups, the resulting deviation after welding differ within each group, indicating that there are other sources of variation present than the introduced disturbances. Those can be variation in material characteristics and other uncontrolled factors during the tests.

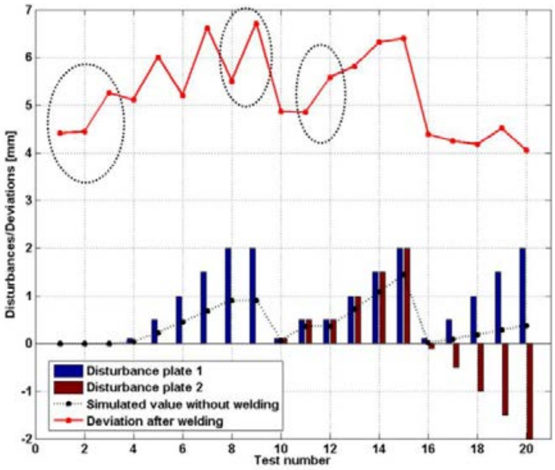

Fig 3: Results from physical tests.

However, also with those uncontrolled variation sources present, there is a clear relation between disturbances on part level and resulting deviation after welding. This is even clearer when looking at Fig 4. Here, the bars show the sum of disturbances on plate 1 and 2. The correlation between the sum of disturbances and the resulting deviation is 0.79, which indicates quite a strong linear relationship.

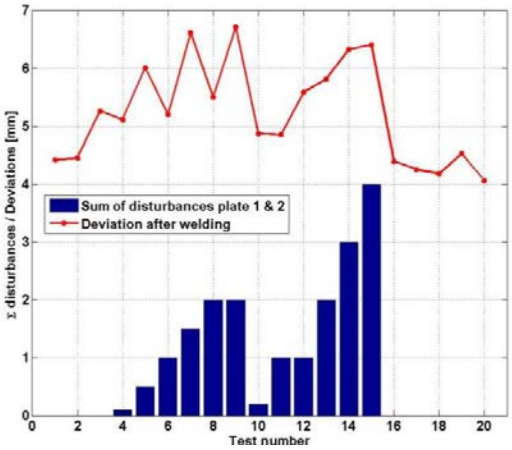

Fig 4: Relation between sum of disturbances and deviation after welding.

Another interesting observation is that the introduced disturbances in test 16-20, which summarize to zero, give rise to no more variation than what is present using nominal plates (test case 1-3). This effect is partly due to the coordinate system transform arising when the inspection is done using locators on plate 1 while measuring is done on plate 2. In Fig. 3 the dotted black line shows this value, i.e. the simulated value if welding is not taken into account. This is however not the complete explanation to the low values for test case 16-20, but there are also effects due to welding.

Generally, geometrical distortion due to the welding process is caused by:

- Volumetric expansion and contraction due to local temperature changes;
- Microstructural phase changes;
- Release and redistribution of pre-welding residual stresses.

For the symmetrical deviations (test case 16-20) the distortions caused by welding seem to be smaller than for the other test cases.

## 5. Predicting variation in welded assemblies

In order to predict the variation of a welded assembly, it is of course most important to include the deformation due to the heat generated during welding. The physical tests in the previous section did show that it is not possible to clamp the part to nominal position before welding to avoid influence from part variation.

It has also been shown [1] that it is not possible to do a welding simulation based on nominal parts and a variation simulation including part and fixture variation and then just combine the results. Instead, in order to capture the non-linear behavior of weld-induced deformation, the welding simulation must be applied to non-nominal parts.

Therefore, to predict the variation in a welded assembly, all factors in Fig 5, including the effects from welding process, should preferably be included in the simulations.

The **part variation** will propagate to the assembly and is therefore an important contributor to variation on assembly level.

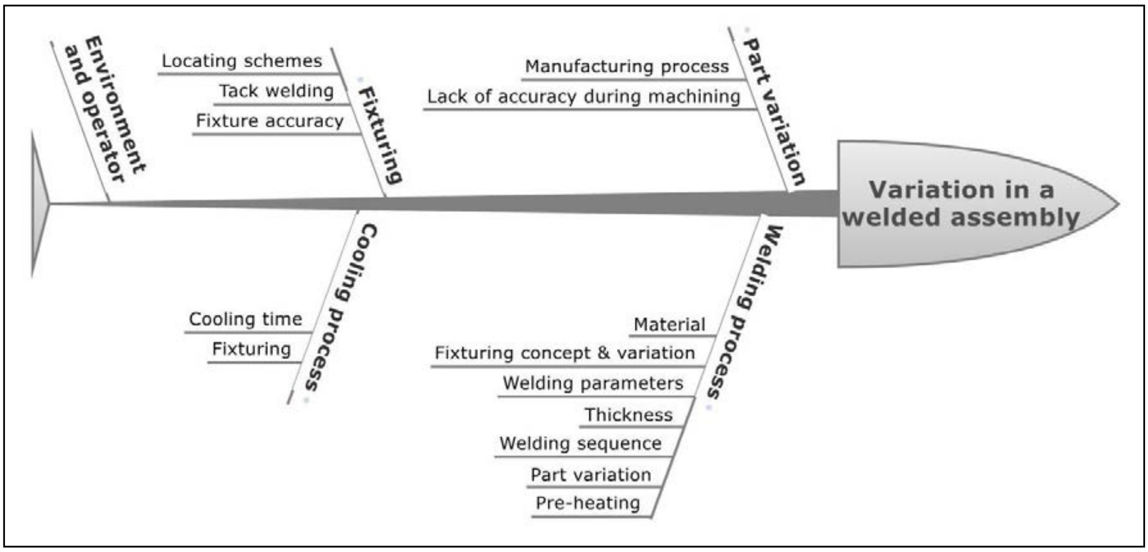

Fig 5: Factors contributing to variation in a welded assembly.

The **fixturing** and the locating schemes during tack welding and welding will affect how the part variation propagates to the assembly. A locating scheme that suppresses variation is said to be robust and a locating scheme that amplifies variation is said to be sensitive. There are tools, such as robustness analyses in commercial software to improve and evaluate robustness of a concept [3, 15-17]. The number and position of tack welds before the continuous welding affects the positions of the parts relative each other. Usually, the tack welding aim at minimizing deviation between parts in the weld line and the tack welds can thereby replace clamps. The sequence of the tack welding does also affect the geometrical result after tack welding. The effect from spot welding sequence in sheet metal assemblies has been treated in a number of papers [18-21].

Also variation in the position of tack welds may affect the results [22]. The fixture accuracy can be judged from a repeatability study of the assembly fixtures and included in the variation simulation [23].

The **environment and operator** will also affect the result. Those factors can however be difficult to include in the simulations. Some work in automotive industry have been done showing how the operator influences geometrical variation in assembled products [24].

The **cooling process** will affect the springback after welding and both the way the parts are fixture during cooling and the allowed cooling time will affect the result [25].

The **welding process** itself is of course of major importance for the final result. But the welding process itself is affected by factors like material, fixturing concept, part variation (as shown in this paper), welding sequence [26] and of course by the welding parameters.

From the fishbone in Fig 5 it can be noted that part variation and fixturing contribute both as main factors but also as indirect factors via the welding process. Those contributors are consequently of vital importance in the geometry assurance process for a welded assembly.

To be able to successfully predict variation of a welded assembly, it is of course also important to define the critical dimensions of the final assembly, i.e. the wanted output. The output must then be compared with requirement in those dimensions. A suggestion of a virtual working procedure for variation simulation and geometry assurance of a welded assembly is:

1. Define the critical dimensions of the final assembly
2. Find locators that optimize robustness during tack welding [27]
3. Optimize tack welding with respect to geometrical outcome by altering welding sequence and the number and position of tack welds.
4. Find locators that optimize robustness during welding [27]
5. Set tolerances on part level
6. Perform a variation simulation including the effect of welding
7. Check capability by comparing predicted outcome and requirement
8. If the result is not satisfying, the tolerances have to be altered, go back to point 5.

In the variation simulation, all sources of variation that affect the final result should, if possible, be included.

## 6. Conclusions

In this paper, the effects from deviations at part level on deviations on assembly level for a welded assembly are investigated. Increased knowledge in this area is an important input for tolerancing and variation simulation and is a key factor for geometry assurance of welded assemblies.

The following conclusions can be drawn:

- Even if the parts are clamped to nominal position in the weld lines, deviations on assembly level (after welding) and deviations on part level (before welding) are strongly correlated.
- If the part deviations on two equal parts, A and B, are equal in magnitude, but have opposite signs, the deviation on assembly level is not affected.
- Welding of nominal parts and welding of non-nominal parts do not give the same results, which is an important input also for welding simulation.

Furthermore, factors contributing to geometrical variation in a welded assembly are listed. It could be noted that part variation and fixturing are recurrent factors, thus affecting the result to a large extent. Those factors need to be included in a variation simulation in order to reach a satisfying result. A working procedure for variation simulation of welded assemblies is also presented.

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