Weld Distortion Optimisation using HyperStudy

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Abstract
Distortion induced in parts due to the cooling of welds complicates automated manufacturing lines in the automotive industry. The resulting deformation leads to additional investment such as end of line machining to correct affected assemblies. Utilising optimisation software a welding pattern can be found which retains the intended performance of a part while reducing the distortion induced from welding. Weld locations may be optimised alongside welding sequence to allow process requirements to be considered within the early design stage. This leads to high performance, low distortion assemblies which can ultimately be manufactured at the lowest possible cost.

Keywords: Optimisation, Welding, HyperStudy, Distortion, Automation, Scripting

1.0 Introduction

Weld distortion is a very significant issue in the manufacture of welded components, especially in the automotive sector where tolerances are tight and complex high performance components are the norm. A typical chassis subframe must achieve +/-0.5mm positional tolerance at its connection points (actually +/- 0.35mm for capable process), whilst withstanding heat from up to 20 meters of welded joints. The contraction caused by the cooling of these welds leads to distortion significant enough to require additional processes to recapture the lost geometry (Figure 1).

With the ever tightening squeeze on budgets as vehicle manufacturers try to cut costs and businesses try to remain competitive, reducing unnecessary processes presents a distinct business advantage. Couple this with the potential to reduce “Cost of Quality” issues by having more reliable and robust builds it becomes apparent that real savings and opportunities could be achieved by exploiting the latest technology to minimise weld distortion.
While process techniques exist to reduce weld distortion by controlling the heat exchange, they add additional cost and complexity to the line which limits savings. The ideal solution would be to minimise the weld distortion without utilising specialist equipment.

Weld distortion can be estimated using Finite Element Analysis (FEA) software. With this, we can then begin to optimise the amount of distortion by strategically removing and balancing weld sections to limit distortion. The objective of this study is to minimise the amount of weld distortion, without adding additional process costs or reducing the performance of the part.

*Figure 1: Production Chassis with Distorted Scan Overlay (100x scaled distortion)*

### 2.0 Weld Distortion Optimisation Method

#### 2.1 Weld Distortion Analysis

A standard shrinkage method developed by Schmidt et al. [1] has been correlated previously on Gestamp chassis parts [2] and used as the basis of the optimisation study. Some correlation results obtained are shown below on a simple bumper beam.

*Figure 2: Simple Bumper beam correlation*

The objective of the analysis used for this optimisation is not to predict the weld distortion with absolute accuracy but to give trends and direction with limited computational resource.

#### 2.2 Weld Distortion Case Study

The BMW MINI front subframe tower, shown below in colour, has been used to demonstrate the weld distortion optimisation approach. The tower is particularly susceptible to distortion due to its tall and thin dimensions. The current, state of the art, approach is to minimise the amount of weld used and design the part with some ‘float’ between components and/or add a post assembly machining operation to guarantee position.
2.3 Weld Distortion Optimisation Approach

The approach taken in this study is to use optimised welding alone to maintain the original geometry. A review of recent literature found very few attempts to optimise distortion through welding, with only one relevant study using a meta-model to reduce computational time to allow a 6 weld sequence to be optimised [3].

Two ways to effectively reduce weld distortion have been considered in this report. Firstly, by creating a fully welded model as a starting point, weld is deleted in short sections, thereby removing weld that is causing severe distortion and provides the opportunity to ‘balance’ welds such that the distortional effects of one weld may be cancelled out or minimised by another. Secondly the welding sequence is altered to change the distortion; this method can be applied after a weld removal optimisation to give an optimal welding procedure (Figure 4).
2.3 Weld Removal Optimisation

Weld removal optimisation (Route A) was investigated using HyperStudy to manage the optimisation algorithms and analysis of results. This was achieved using HyperStudy to manage the optimisation which passed a set of comma separated values to activate or deactivate welds represented by a 1 or 0 value respectively as shown below.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Weld01</th>
<th>Weld02</th>
<th>Weld03</th>
<th>Weld04</th>
<th>Weld05</th>
<th>Weld06</th>
<th>Weld07</th>
<th>Weld08</th>
<th>Weld09</th>
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</tr>
</tbody>
</table>

A SciLab script [4] then interpreted these values and created an ABAQUS deck to be solved with only the requested welds appearing in the model. Next a batch file was used to send the deck to an external Linux cluster to be solved. The results from which were read into HyperStudy to give feedback in future runs.

An optimisation based approach was adopted as brute force evaluation of all weld combinations proved prohibitively computationally costly as, even in a small tower investigation, the many design variables generated by splitting the welds into short 40mm sections gave total run times in excess of the entire project development time. Furthermore, a design of experiment (DOE) approach was not appropriate as there was no need to map the entire design space but focus on one particular region (mostly welded) which was dealt with appropriately by the optimisation algorithm.
Finally an initial topology optimisation was carried out with constraints on stress and stiffness to identify a small number of critical welds that would help prevent a zero weld – zero distortion solution.

![Figure 6: Weld sections undergoing optimisation](image)

The objective of this optimisation was to minimise the distortion of the tower measured by the displacement of the top of the tower as the weld sections cool (Figure 3). To prevent the optimisation algorithm from removing too much weld and compromising the structural integrity of the tower in pursuit of minimal distortion a constraint on the tower stiffness under loading was introduced.

$$\text{minimise } \text{Distortion}$$
$$\text{subject to } \text{Stiffness} > \text{target } kNmm^{-1}$$

The initial optimisation algorithm used was an Adaptive Response Surface Method (ARSM) managed by HyperStudy. The use of which was prudent as, for an initial optimisation run, the fast convergence of a gradient based optimisation algorithm at the expense of only finding a local solution was preferable to swiftly prove the concept. The process used is illustrated below.

![Figure 7: Optimisation Process](image)

After the ARSM algorithm gave a local solution to the optimisation problem, a genetic algorithm was run to investigate the possibility of a better global solution. The genetic algorithm was selected as it is a highly parallel algorithm allowing the full utilisation of multiple machines within a cluster and due to its applicability to discrete problems. However
the number of iterations required to find a global optimum proved to be too computationally costly.

A Hybrid Method Multi-Objective (HMMO) was then utilised (with a single objective) as a compromise between the two algorithms as it utilises both gradient and global searching algorithms. The HMMO gave the same solution to the problem as the ARSM algorithm, indicating that the ARSM solution was the global optimum for the given stiffness constraint.

Next the HMMO algorithm was used to investigate the Pareto frontier of design solutions, tasked with optimising both stiffness and distortion it found the curve of optimal designs within a given range.

Detailed durability analysis was then run to check that the proposed design’s performance was acceptable.

2.4 Weld Sequencing Optimisation

The sequence in which a part is welded has a significant effect on the distortion of the part as the stiffness changes significantly depending upon which welds have already been executed. To investigate the significance of this effect a second HyperStudy optimisation was set up to optimise the sequence of welding to give minimal distortion of the tower. This optimisation could be left unconstrained as the welds used were fixed from the previous optimisation and cannot be removed, allowing the tower to retain the same stiffness found from the previous analysis.

This method was achieved by utilising HyperStudy to swap weld’s order in the welding sequence by allowing every weld to take a variable in the range 0 to No. welds - 1. This number represents how many indexes further ahead the weld should swap with. For example:

<table>
<thead>
<tr>
<th>HyperStudy Variable Management</th>
<th>Scilab Sequence Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iteration</td>
<td>Weld01</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
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<tr>
<td>4</td>
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<tr>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>...</td>
</tr>
</tbody>
</table>

*Figure 8: Weld Sequence Generation Example*

SciLab scripts were used to implement this into solvable decks and batch files used to solve the decks on the cluster in a similar manner to the weld removal optimisation.

However this method links the variables as they all affect each other’s position in the weld sequence and allows for repeated designs given different inputs.

3.0 Optimisation Results

3.1 Weld Removal Optimisation

Topology optimisation identified 20% of the total welds which were critical for the stiffness and strength of the tower while inducing minimal distortion. These welds were then fixed in place (they were still modelled as shrinking elements but could not be removed by HyperStudy) during subsequent analysis in order to increase optimisation convergence. The remaining 80% welds were then taken forward into the optimisation loop for weld removal to consider distortion and are shown below in figure 9.
The original tower distortion due to welding is shown below. The welds are distributed on the structure such that distortion in the y direction dominates; however x and z distortions are also significant leading to an overall displacement of 1.24mm at the top of the tower. The balancing of the distortion in the y direction is limited as the tower is only welded on its inner edge, not outer edge, but can be minimised by removing some of these welds. The x and z directions however eminently represent a balanceable problem.
The final tower distortion due to welding is shown above. The stiffness under loading was equivalent to the original model but with significantly reduced distortion. The only remaining distortion is \(0.542\text{mm}\) in the \(y\) direction with the \(x\) and \(z\) components being essentially zero due to weld distortion balancing.

The Hybrid Method Multi-Objective (HMMO) optimisation generated a Pareto front of designs shown below. However this was generated at significant computational expense.
The peak stress analysis showed that the new proposed design also outperformed the old design in terms of the maximum stress induced in the tower under an envelope plot of 14 different load cases.
3.2 Weld Sequencing Optimisation

The weld sequence optimisation lead to a further 71% (0.157mm) distortion reduction to the removed weld optimised design using the ARSM algorithm. Very little robust convergence was observed with the solution being a local optimum.

![Figure 15: Convergence of ARSM](image)

The genetic algorithm utilised again gave very long run times with convergence to the global optimum solution being likely but prohibitively computationally costly. However from the completed runs the best sequence gave a distortion of only 0.0856mm. Which, given the accuracy to which we are working, is acceptable to use as the optimum in the proposed welding procedure.

![Figure 16: Genetic Algorithm Iterations](image)
The results from the optimum sequence obtained by GA algorithm are shown below.

![Contour Plot](image)

**Figure 17: Weld Sequence Optimised Distortion**

<table>
<thead>
<tr>
<th></th>
<th>Original design</th>
<th>Weld Removal Optimised design</th>
<th>Weld Sequence Optimised design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weld distortion (mm)</strong></td>
<td>objective</td>
<td>1.24</td>
<td>0.542</td>
</tr>
<tr>
<td><strong>Stiffness (MNmm⁻¹)</strong></td>
<td>constraint target (27.4)</td>
<td>30.1</td>
<td>27.4</td>
</tr>
<tr>
<td><strong>Max Stress (MPa)</strong></td>
<td>Constraint target (280MPa)</td>
<td>280</td>
<td>234</td>
</tr>
<tr>
<td><strong>Weld length (mm)</strong></td>
<td>output</td>
<td>870</td>
<td>650</td>
</tr>
<tr>
<td><strong>Total Robot head movement (mm)</strong></td>
<td>output</td>
<td>1290</td>
<td>1140</td>
</tr>
</tbody>
</table>

**Figure 18: Results Summary**

### 4.0 Optimisation Discussion

#### 4.1 Weld Removal Discussion

The weld removal optimisation worked well giving a 56% reduction in the distortion predicted at the top of the tower for an equivalently stiff and durable design. Fast convergence to a global optimum with the ARSM optimisation algorithm allows this algorithm to be applied to larger problems such as a full subframe without need for a DOE to reduce the number of design variables.

The Pareto frontier generated from the HHMO optimisation gives a useful insight into the optimal designs around a given range of specifications; this could be used to swiftly adapt designs in the face of changing design targets but at the cost of significant computational expense.

This method is also best applied to areas in which welds can be ‘balanced’ such that the distortional effects of one weld may be cancelled out or minimised by another.
4.2 Weld Sequencing Discussion

The weld sequencing optimisation gave vastly reduced distortions resulting in a welding process with a predicted 93% reduction in distortion.

However for this to be realised more detailed modelling of the constraints used in manufacturing is required. Additionally the convergence observed by both optimisation algorithms was poor which is a problem as a weld order deck takes significantly longer to solve than a weld removal deck. This poor convergence could be due to the weld swapping algorithm used in SciLab as this inadvertently links the variables, such that changes to one variable significantly affects another, together making true optimisation difficult to achieve.

A better method may be to implement continuous variables to all the welds under consideration and order them in terms of magnitudes of this variable.

4.3 Further Investigation

This investigation into the reduction of weld distortions could be extended by introducing additional enhancements both in optimisation procedure and thermo-mechanical simulation. These could include:

- Run a detailed weld distortion simulation on the proposed optimal welding procedure to check the accuracy of the modelling approximations e.g. moving heat source.
- Correlate results on a manufactured part to validate this approach.
- The inclusion of an estimate of the time taken to weld the proposed weld sequence so as not to violate the required cycle time.
- Develop a method to prevent repeated weld sequences to make the optimisation loop more robust.

5.0 Conclusions

- The use of optimisation software to minimise weld distortion can lead to a welding procedure that produces high performance, manufacture friendly assemblies without expensive tool changes.
- More thorough structural integrity checks should be undertaken to ensure the design is wholly suitable for the application.
- More constraints on optimisation (Max stress, multidirectional stiffness) would help to ensure that proposed designs were more suitable for the application.
- Gradient based optimisation techniques apply well to weld removal problems however their applicability in weld sequencing problems is limited where global search algorithms are more effective.
- HyperStudy allows flexible, multi-platform optimisation management.
- The platform developed is generic and applicable to any weld distortion project without any adaptation.

6.0 References

