A METHOD TO IMPROVE EFFICIENCY IN WELDING SIMULATIONS FOR SIMULATION DRIVEN DESIGN

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ABSTRACT
Welding is one of the most commonly used methods of joining metal pieces. In product development it is often desirable to predict residual stresses and distortions to verify that e.g., alignment tolerances, strength demands, fatigue requirements, stress corrosion cracking, etc. are fulfilled. The objective of this paper is to derive a strategy to improve the efficiency of welding simulations aiming at a (future) simulation-driven design methodology. In this paper, a weld bead deposition technique called block dumping has been applied to improve the efficiency. The proposed strategy is divided into seven steps, where the first four steps are verified by two welding simulation cases (a benchmark problem for a single weld bead-on-plate specimen and a T-welded structure). This study shows that by use of the block dumping technique, the computation time can be reduced by as much as 93% compared to moving heat source, still with acceptable accuracy of the model.

1 INTRODUCTION
Welding is one of the most commonly used methods of joining metal pieces. In fusion welding, the metal pieces are heated until they melt together, leading to strong coupling between thermal, mechanical and metallurgical (microstructural) properties. Due to the complexity of the welding applications, the governing equations as well as the thermal, mechanical and metallurgical couplings, computational support is necessary for prediction of distortions and residual stresses. The development of the field of computational welding mechanics has been well described by, for example, Karlsson [1], Goldak and Akhlagi [2] and Lindgren [3-5]. A lot of research has focused on predictions of residual stresses and distortions due to welding of metal pieces of different shapes and material properties [6-9].

Several reports concern validation of predictions of residual stresses and deformation [10-13]. The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) formed a benchmark problem for a single weld bead-on-plate specimen [14]. NeT-members have then, by use of Finite Element simulations, predicted and measured residual stresses and thermal fields of this benchmark problem by different methods, of which the results have been compiled by Smith et al. [15, 16]. In these reports, different sources of errors are discussed and the conclusion is that “there is much room for improvement” regarding prediction accuracy.

In product development it is often desirable to predict residual stresses and distortions to verify that e.g., alignment tolerances, strength demands, fatigue requirements, cracking, etc. are fulfilled. For example, it is important to keep track of the residual stress- and deformation history when simulating a sequence of manufacturing processes [17, 18]. Different approaches have been developed for how to use welding simulations to predict suitable sequences of weld paths. Troive et al. [19] compared different predefined paths while Voutchkov et al. [20] used surrogate models to solve a combinatorial weld path planning problem. Further efforts have been made to show how deposition sequences affect, for instance, residual stresses and distortions [21]. Guirao et al. [22] present a methodology in which, depending on the size of the problem, two different simulation strategies are proposed. In this methodology, a direct technique is used for models with 150,000 degrees of freedom or less, while a sub-structuring technique of the linear behavior parts in the model are used for larger size models. Guirao et al. concluded that their proposed
model led to high efficiency regarding calculation time and applicability to complex problems.

Although a lot of research has been conducted on welding simulations, there is still a need for more efficient welding simulation approaches and methodologies for how to use such simulations to support design processes. Hence, the objective of this paper is to derive a strategy to improve the efficiency of welding simulations aiming at a (future) simulation-driven design methodology.

In this work, Goldak Technologies modeling and simulation software VrWeld [23] has been used to demonstrate the proposed strategy.

2 THEORY
This chapter describes the theory behind the fast simulation option available in VrWeld, which is a welding simulation program developed by Goldak Technologies Inc. A method for how to use these fast simulations is also proposed.

2.1 Time Efficient Welding Simulations
When conducting transient welding simulations to predict e.g., residual stresses and deformations, a Gaussian Ellipsoid heat source (Figure 1) is commonly used [2]. The calculation time for such a transient simulation is today at a level that often allows a designer to test different welding approaches at an acceptable time cost. However, when several simulations have to be conducted, for example, during design of experiment (DoE) and optimization or in cases where long welds are simulated, the calculation time can become a problem. One way to significantly decrease the simulation time is to deposit the whole weld bead or large pieces of the weld bead in a single time step; i.e., heat is applied and elements of the weld piece are activated in one time step. The number of weld bead deposition steps will from now on be referred to as number of block dumps. Block dumps are always followed by a number of cooling time steps. Different types of heat sources can be used for welding simulations e.g., prescribed temperature [2] or power density models such as the Gaussian Ellipsoid [2]. The accuracy of block dump welding simulations depends on the number of block dumps. A higher number of block dumps gives a higher accuracy, though at the cost of calculation time. A suitable compromise between accuracy and calculation time is needed. The suitability of such a compromise depends on the welding case.

2.2 Proposed Welding Simulation Strategy for Improved Efficiency
In order to improve the efficiency of welding simulations, a simulation strategy of seven steps is described below.

1. **Welding and material parameters.** Gather information about the real welding process such as welding method, welding speed, welding power and welding efficiency. The material parameters include thermal and mechanical properties.

2. **Geometry and preprocessing.** Create CAD geometries of welded parts and, possibly, each weld and import them into the welding simulation software (STL-files in VrWeld) where the initial simulation mesh is created. Another approach is to create the initial mesh with external software and then import it into the welding simulation software (ABAQUS is one example of a mesh format supported in VrWeld). Define mechanical and thermal constraints, material models and weld paths. Apply the boundary conditions and external loads on the mesh.

3. **Calibration.** a) Calibrate the heat input model, for example, by results from thermocouple measurements or weld cross section samples. b) Calibrate the mesh for a suitable compromise between accuracy and calculation time. Notice that this compromise is case dependent. This is normally done by running 3 or more simulations with varying mesh density and then evaluating how the result converges.

4. **Deciding number of block dump.** Run a series of block dump weld simulations with varying numbers of block dumps. Five cooling time steps have been used in the examples presented in this paper. Compare the results from the moving heat source simulation with the block dump simulation results to evaluate how many block dumps are needed to achieve the needed accuracy of the simulation. If a moving heat source simulation will be too time-consuming, the needed number of block dumps can be decided by observing result convergence for an increasing number of block dumps. The level of accuracy is often case specific. Therefore, the decided number of block dumps can be applicable for similar products.

5. **Design Space Exploration (DSE).** Use the decided number of block dumps in welding simulations to evaluate each iteration in the design space exploration analysis i.e., DoE, optimization, etc.

6. **Verifying results with moving heat source simulation.** Compare the final result from the DSE to a simulation with a moving heat source or with an increased number of block dumps to ensure that results obtained in the previous step are accurate enough.

7. **Physical testing and/or manufacturing.** Proceed with physical testing and/or manufacturing based on the results obtained from welding simulations. The amount of physical testing should at this stage have been reduced compared to a situation where no welding simulations have been performed.
3 VERIFICATION CASE 1: NeT BENCHMARK

As a part of the mission to develop experimental and numerical techniques and standards for the reliable characterization of residual stresses in structural welds, the NeT formed a Round-Robin benchmark problem [14]. The benchmark problem consists of a 60 mm long single weld bead on the top surface on an austenitic steel plate, see Figure 2. Four nominally identical plates (A11, A12, A21 and A22) were welded under controlled conditions and the temperature history was measured by nine thermocouples (T1-T9), seen in Figure 2. Several NeT members from different organizations/institutes then performed residual stress measurements along lines A to D in Figure 2 on the four specimens using various methods which are presented in Table 1. Welding simulations have further been performed by a number of members whereby the temperature history of the thermocouples and the residual stresses have been analyzed in different ways (see Table 1). A compilation of these measurements and simulation results has been made by Smith [15, 16].

3.1 Step 1 and 2

In the NeT benchmark problem all data regarding the welding process are available. A CAD geometry of the plate was created in CAD software and then exported to VrWeld in STL format. An initial mesh including the weld bead was then created directly in VrWeld and the plate was then restrained according to Figure 6, which prevents rigid body motion without restraining the growth/shrinkage of the plate. In reality the plate was transversally restrained by a vice. However, Smith [16] suggests that an unrestrained plate can be used for the residual stress analysis, since simulations with a full contact transversal restraint predicted similar results as for an unrestrained plate.

3.2 Step 3

a) The parameters of the Gaussian ellipsoid heat source shown in Figure 1 were calibrated by use of measured temperatures shown in Figure 3. The calibrated parameters are presented in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian ellipsoid heat</td>
<td>$a_1 = 4$ mm</td>
</tr>
<tr>
<td>source parameters</td>
<td>$a_2 = 1$ mm</td>
</tr>
<tr>
<td></td>
<td>$b = 0.5$ mm</td>
</tr>
<tr>
<td></td>
<td>$c = 12$ mm</td>
</tr>
<tr>
<td>Power</td>
<td>1437 W ($7.2 \text{ V}, 200 \text{ A}$)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>80%</td>
</tr>
<tr>
<td>Dwell time</td>
<td>1 s</td>
</tr>
<tr>
<td>Weld speed</td>
<td>2.27 mm/s</td>
</tr>
</tbody>
</table>
Figure 3 shows a comparison of simulation results and measurements from thermocouples T1-T9 after calibration of heat input parameters.

Figure 3. SIMULATED TEMPERATURE (DASHED LINE) COMPARED TO THERMOCOUPLE MEASUREMENTS.

b) To determine the required mesh density a mesh convergence analysis was performed. Four meshes with varying mesh density, shown in Table 3, were created and the simulation results were compared. Figure 4 shows the residual stresses along line D3 (which is positioned longitudinally 3 mm underneath the surface at weld center) for these meshes. Similar results were observed for lines B-D, B2 and D2.

Table 3. NUMBER OF ELEMENTS IN MESHES.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>13370</td>
</tr>
<tr>
<td>Medium 1</td>
<td>39462</td>
</tr>
<tr>
<td>Medium 2</td>
<td>74978</td>
</tr>
<tr>
<td>Fine</td>
<td>105838</td>
</tr>
</tbody>
</table>

From Figure 4 it can be concluded that for stress calculations a finer mesh than the Medium 2 mesh will not give a more accurate result. Therefore, the Medium 2 mesh was used for this benchmark. Notice that for another case, a coarser mesh could be accurate enough.

The Medium 2 mesh cross-section was created based on the sample cross-section seen in Figure 5. The width and height of the weld are approximated to 8 and 0.75 mm. Notice the thermocouple hole in the sample piece shown in Figure 5.

The total Medium 2 mesh can be seen in Figure 6. The mesh is denser closer to the weld, and as Smith [16] suggested, this denser area goes through the whole plate. In this case study, the whole plate is meshed, while symmetry was used in the simulations conducted by the NeT members. The weld bead mesh runs along the whole plate, but only the mid third is heated in the simulations.
Figure 7 shows a comparison between test sample and calibrated simulation fusion boundaries. The red contour in the simulation picture shows the material that reaches the metal’s melting point, which is approximately 1400°C.

3.3 Step 4

As a reference, simulations with a moving heat source were carried out. The residual stresses are presented along lines B-D, B2 and D2 and in Figure 2. Line B-D is positioned at the center of the plate and the residual stress is presented from the bottom to the top surface. Line B2 is positioned transversally 2 mm underneath the surface at weld mid length. The presented residual stresses start from the thermocouple side. Line D2 is placed longitudinally 2 mm underneath the surface at weld center. The residual stress is presented from the weld start. Figure 8 to Figure 13 shows a comparison of the NeT Round Robin results and the results obtained in VrWeld with moving heat source (green line).
All results shown in Figure 8 to Figure 13, except those related to VrWeld simulations i.e., green lines, are extracted from Smith [15, 16] where more detailed information regarding results can be found. Notice that the VrWeld simulation results generally show better agreement with the measurements compared to the other simulations.

For the NeT benchmark case, to find a suitable number of block dumps i.e., that reduces the calculation time and still gives sufficient accuracy, a series of simulations with four different block dumps was carried out (1, 2, 4 and 10 block dumps). In Figure 14 to Figure 19 simulated residual stresses are shown for the moving heat source as well as for the block dumped simulations.
Table 4 shows the standard deviation of the difference between the block dumped simulations and the moving heat source simulation. The standard deviation is calculated according to Equation 1, where \( x \) is the difference between the moving heat source and the blocked dumped simulation result vectors i.e., the transversal and longitudinal residual stress values along lines BD, B2 and D2.

\[
s = \left( \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{\frac{1}{2}}
\]  

(1)

Note that most of the standard deviations decrease with the number of block dumps. However, for some weld paths the standard deviation instead increases with number of block dumps. Notice that even with an infinite number of block dumps, the result would not converge to the moving heat source simulation, since the algorithm for how to apply blocked dumped heat is slightly different compared to a moving heat source. The moving heat source uses the double ellipsoid shown in Figure 1, while the block dumps have a constant heat distribution, although the amount of heat added to the structure is the same with both methods.

Table 5 shows how the calculation times for different numbers of block dumps. All calculation times have been normalized with the moving heat source.

<table>
<thead>
<tr>
<th>Table 5. NeT BENCHMARK CALCULATION TIMES.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation time</td>
</tr>
<tr>
<td>Moving heat source: 100%</td>
</tr>
<tr>
<td>1 block dump                             7%</td>
</tr>
<tr>
<td>2 block dumps                            10%</td>
</tr>
<tr>
<td>4 block dumps                            18%</td>
</tr>
<tr>
<td>6 block dumps                            19%</td>
</tr>
<tr>
<td>8 block dumps                            20%</td>
</tr>
<tr>
<td>10 block dumps                           25%</td>
</tr>
</tbody>
</table>

4 VERIFICATION CASE 2: T-WELD

In many situations distortions are critical to control in welded structures. In order to verify the efficiency of the
proposed strategy a second case of a T-weld joint is also studied, see Figure 20. T-Welded joints are common in industrial applications.

4.1 Step 1 and 2

Figure 20 shows two 20 mm plates that are joined by two fillet welds, W1 and W2. These two welds have a throat size of 6 mm and are welded sequentially in opposite directions i.e., first W1 and then W2. Laying the two welds in the same direction would result in smaller distortions. However, in this study a worst-case scenario has been chosen to highlight the efficiency of the proposed simulation strategy. The x-, y- and z-displacements for the nodes P1 and P2 are used for the evaluation as well as the angles $\alpha_1-\alpha_4$, which are calculated based on the xy-coordinates from points P3-P10, see Figure 20. The material used in both the weld bead and the plates is the material used in [24]. A CAD geometry of the plates was created in CAD software and then exported to VrWeld in STL format. An initial mesh including the weld beads was then created directly in VrWeld and the plate was then restrained according to Figure 20, which prevents rigid body motion without restraining the growth/shrinkage of the plate.

4.2 Step 3

a) The Gaussian Ellipsoid heat source parameters (Figure 1) are adopted from a previous study with similar conditions [25]. Table 6 shows the calibrated heat input parameters.

Table 6. HEAT SOURCE PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian ellipsoid heat source parameters</td>
<td>$\alpha_1 = 10$ mm</td>
</tr>
<tr>
<td></td>
<td>$\alpha_2 = 6$ mm</td>
</tr>
<tr>
<td></td>
<td>$b = 6$ mm</td>
</tr>
<tr>
<td></td>
<td>$c = 8$ mm</td>
</tr>
<tr>
<td>Power</td>
<td>10880 W</td>
</tr>
<tr>
<td></td>
<td>(34 V, 320 A)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Weld speed</td>
<td>37 cm/min</td>
</tr>
</tbody>
</table>

b) Results from four meshes with varying density were compared to ensure that the results converge. The resulting mesh is shown in Figure 21. The final mesh has 27032 elements.

4.3 Step 4

Figure 22 shows the resulting distortions from the moving heat source simulation at 20 times magnification. In Figure 23 to Figure 25, displacements as a function of number of block dumps and the moving heat source results are shown.

Figure 21. RESULTING ANALYSIS MESH.

Figure 22. RESULTING DEFORMATION, DISPLACEMENTS MAGNIFIED 20X.

Figure 23. DISPLACEMENTS IN P1 AS A FUNCTION OF NUMBER OF BLOCK DUMPS COMPARED TO MOVING HEAT SOURCE RESULTS.
Figure 24. DISPLACEMENTS IN P2 AS A FUNCTION OF NUMBER OF BLOCK DUMPS COMPARED TO MOVING HEAT SOURCE RESULTS.

Figure 25. DISTORTION ANGLES AS A FUNCTION OF NUMBER OF BLOCK DUMPS COMPARED TO MOVING HEAT SOURCE RESULTS.

Table 7. T-WELD CALCULATION TIMES.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Calculation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving heat source</td>
<td>100%</td>
</tr>
<tr>
<td>1 block dump</td>
<td>10%</td>
</tr>
<tr>
<td>2 block dumps</td>
<td>11%</td>
</tr>
<tr>
<td>4 block dumps</td>
<td>18%</td>
</tr>
<tr>
<td>6 block dumps</td>
<td>20%</td>
</tr>
<tr>
<td>8 block dumps</td>
<td>28%</td>
</tr>
<tr>
<td>10 block dumps</td>
<td>31%</td>
</tr>
<tr>
<td>14 block dumps</td>
<td>37%</td>
</tr>
<tr>
<td>18 block dumps</td>
<td>47%</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS AND FUTURE WORK

The first case (NeT Benchmark) shows that it is possible to predict residual stresses in VrWeld with good accuracy compared to the NeT measurements and simulations. It also shows that good residual stress predictions can be made with as little as one or two block dumps. When ten block dumps are used the results are practically identical to those of a moving heat source simulation. In this and similar applications, two or more block dumps are recommended, since that gives an acceptable accuracy with up to 90% reduction in calculation time compared to the moving heat source. The first case also shows that, for these kinds of residual stress simulations, the calculation time can be reduced by as much as 93% when using the block dumping method instead of a moving heat source.

The second case (T-Weld) shows that it is possible to use the proposed strategy to predict welding distortions in a T-weld joint. The T-weld case requires more block dumps compared to the NeT case in order to achieve the same accuracy as obtained when using a moving heat source. In this and similar applications, ten or more block dumps are recommended, since that gives an acceptable accuracy with up to 69% reduction in calculation time compared to the moving heat source.

From the results from the two verification cases presented in this paper, it can be concluded that the first four steps of the proposed methodology result in efficient weld simulations with retained accuracy by means of residual stresses and distortions.

Future work will aim at verifying steps five to seven in the proposed strategy. If that is successful a simulation-driven methodology for welded designs will be available.

ACKNOWLEDGMENTS

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