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Mitigation of weld residual deformations by weld sequence optimization: limitations and enhancements of surrogate models

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Abstract

In this study, the use of a surrogate model to mitigate welding deformations in two simple but fundamental geometries, namely plates and pipes, respectively connected by a symmetrical 8 beads X-weld is investigated. Reasons why straight forward utilization of a surrogate model cannot give reliable results in these two cases are precisely pointed out and modifications are introduced to correct the problem. The enhanced algorithm is then shown to accurately predict displacements and to find the bead sequence giving the smallest possible displacement.

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1. Introduction

Among all possible joining methods, fusion welding is still by far the most widely used. During the process, material in and around the weld experiences expansion at heating and contraction at cooling which generates unwanted residual stresses and residual deformations. A variety of techniques have been developed over the years to minimize stresses and deformations but for welds consisting of several passes, bead sequence is one of the most important parameters as it strongly affects the final stress and deformation states, see Mochizuki et al. (2000) and Sattari-Far et al. (2008).

In order to avoid costly and time consuming trial and error welding experiments, numerical simulations based on the Finite Element Method are extensively used to predict residual stresses and deformations. Usually a thermal analysis is first carried out to capture the time dependent temperature distribution in the welded structure and these results subsequently serves as an input for a mechanical analysis. Depending of the size of the model and the number of beads, the total simulation time can vary from one to several hours for a two dimensional analysis and from one to several days for a three dimensional analysis. To be reliable, optimization techniques must cover the full range of possible combinations. Unfortunately the number of combinations grows very fast with the number of alternatives. A simple symmetrical eight beads X-weld (see Fig. 1) connecting two pipes together can for example be welded in 560 different ways (symmetry being taken into account).

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Fig. 1. Cross section of a multi-bead X-weld.

Simulation of the whole set of combinations is therefore unfeasible and use of a surrogate algorithm is mandatory. Surrogate models make use of a very limited but carefully chosen set of combinations to approximate the behaviour of the complete set. Only a few simulations need to be run and use of intermediate and final results in the optimization algorithm allows to minimize the value of a specific outcome: maximum residual stress or deformation for example. In several applications, where events are of the same order of magnitude and do not strongly depend on each other, results are remarkably good. Unfortunately in cases where some events dominate and drastically modify the influence of other events, surrogate models tend to behave poorly. A typical example of such an event is a sudden stiffening of the structure caused by the addition of one particular bead. In such cases, the straight forward standard procedure fails and improvements are necessary.

2. Surrogate models

The principles of optimization by use of *genetic algorithms*, precursors to surrogate models, are exposed in details in Goldberg (1989). The three steps of the method: Reproduction, Crossover and Mutation, are applied in Kadivar et al. (2000) to the welding of an inner circular plane plate inside of an outer circular hollow plate. The weld consists of one single pass divided into 8 arcs of equal length. The sequence leading to the smallest displacement at the outer edge of the outer plate is computed and shown to agree well with available experimental data. The genetic algorithm method is further developed in Voutchkov et al. (2005) based on the concept that the effect of a certain welding event mostly depends of the few previous welding events. The smallest possible number of complete welding sequences ensuring that every welding event, at one or all possible positions in the sequence, is preceded by all other possible welding events, one or several levels below, is generated. Actual simulations of these specific sequences are carried out and data is stored after each welding event. This data is then used to estimate welding effects of all welding events in the entire list of complete welding sequences. Welding of a vane in a Tail Bearing House is used as an illustration of the method. The single pass is divided into 6 smaller welds and out of 46.080 possible combinations ($6!*2^6$), only 27 need to be actually simulated. The welding sequence leading to the smallest displacement is sought for and successfully computed. In Asadi et al. (2011), straight forward use of this method is applied to displacements in a pipe butt weld consisting of two weld layers made up of three sub passes each. The 6 combinations for the first layer are simulated but for the second layer, only 14 combinations out of 46 ($3!*2^3$) need to be investigated. In a similar manner, in Asadi et al. (2015), two stiffeners are welded perpendicularly to a plate. Both stiffeners are welded on both sides rendering 384 welding combinations ($4!*2^4$) out of which 28 need to be simulated. In this case, optimization aims at minimizing warpage.

Throughout this paper, the method presented in Voutchkov et al. (2005) is used with the same notations and the same definitions for *order* and *type* of contribution. Order refers to the number of previous events that are accounted for to evaluate the effect of the current event; type (1 or 2) indicates if the position of the current event is the same as in the simulated sequence. Clearly, higher orders and type 1 contributions should lead to better optimizations but not surprisingly request a larger number of simulations. Here, focus is on second order of type 2 contributions, meaning that only the influence of the event immediately preceding the current event is taken into account and that the position of this pair of events in the whole sequence is ignored. The R_2" matrix defined in the literature (where 2 is the order and " the type) keeping track on how many times two specific welds follow each other is here simply called, the *Pair matrix* and the *Design of Experiments (DoE)* table the *Selected runs* table.

3. Finite element model

The finite element models used here to carry out welding simulation are two dimensional and consist of two distinct steps: a thermal analysis followed by a mechanical analysis. The finite element procedure simulates the successive addition of molten metal that cools in a sequence of transient thermal analyses and elastic-plastic analyses. Deposition of the liquid weld pool is modeled