Key issues of computational weld mechanics with applications

F. W. Brust[1], and J. C. Kennedy[1]

Summary

The computational modeling of manufacturing processes has emerged as a key enabling technology for industry. Once a manufacturing process model is developed and validated it can be used to optimize performance and reduce fabrication costs. Welding remains the main fabrication process for metallic structures. A comprehensive computational weld model is discussed here. Several examples illustrating the advantages of computational weld modeling as used in a manufacturing environment is presented.

Introduction

Computational weld modeling is challenging because many of the processes of welding are highly nonlinear. Material melts and re-solidifies, very high transient thermal gradients are experienced, non-linear temperature dependent plastic straining and phase transformations occur, among other sources of nonlinearity. Moreover, for weld modeling to have practical advantages in industrial production, computational solution times must be manageable since an optimum weld design of large, complex fabrications requires numerous separate analyses. References [1-3] (and references discussed therein) overview some of the modern computational weld models developed to date.

There are two ways weld modeling can have an impact on weld fabrications: (i) distortion control and (ii) residual stress control. Distortion control is a key performance goal enabler and fabrication cost control advantage. Large ship panels, earth moving machines, Maglev tracks, engine components, nuclear power plant components, etc. often have strict distortion control requirements. Straightening 'after build' can be very expensive, and in some cases, not possible. Residual stress and microstructure control can lead to improved fatigue and corrosion performance, and improve service fracture response. Computational weld modeling can, and has been used to devise practical manufacturing fabrication procedures to control both of these. Control methods include weld sequencing, heat sink welding, pre-camber methods, and thermal tensioning.

Computational Weld Mechanics and a Model

The weld modeling process is illustrated in following steps. Figure 1 illustrates the computational weld methodology.

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[1] Battelle Memorial Institute, Columbus, Ohio, USA

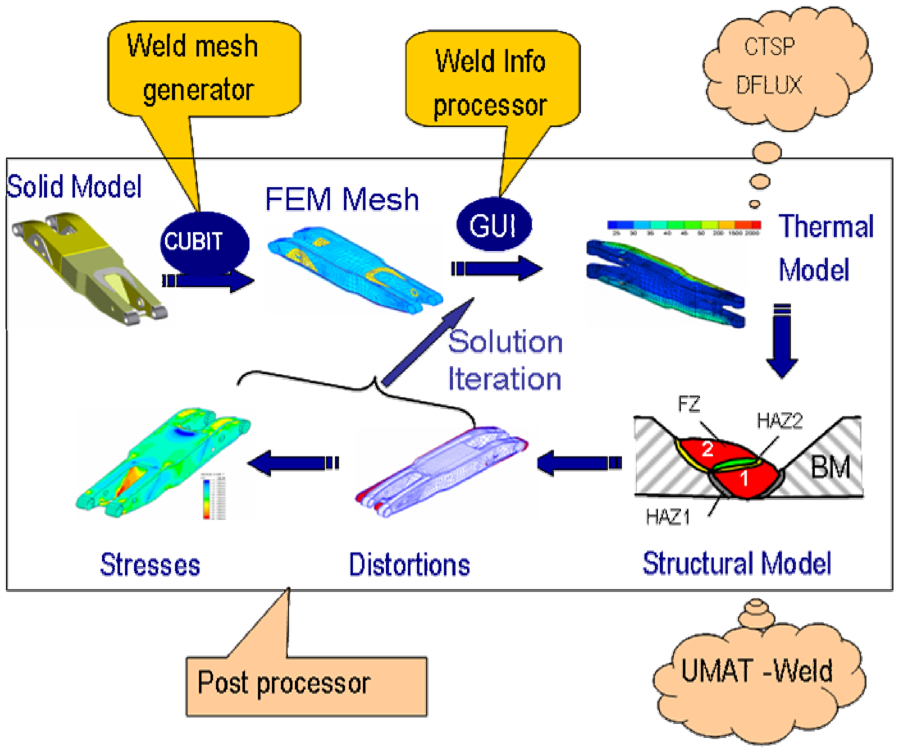

Figure 1. Welding Simulation Flow.

This represents a boom in large earth moving machine. Typically a solid model of the structure is first converted into a finite element grid that is tailored for weld modeling. The weld procedure information is then defined. This would include the weld sequence, weld type, whether there are heating or trailing thermal sources (for instance, for heat sink welding or thermal tensioning), etc. For large structures with hundreds of meters of weld deposition, the use of a GUI to define the welds and automatically modify the weld sequence to set up different optimization analyses is convenient.

The next step represents the determination of the temperature versus time fields that are modeled for each weld pass that is deposited. As seen in Figure 1, one can do this numerically by writing a 'flux' algorithm (called DFLUX within ABAQUS) that properly represents the heat flux distribution from the weld torch. However, it turns out that such numerical thermal solutions are very time consuming and render the solution of large problems impractical for industrial use. A series of closed form analytical solutions can represent the heat input from welding very accurately (Reference [3]). These new solutions, called CTSP in Figure [1] (Comprehensive Thermal Solution Procedure), are orders of magnitude faster than numerical solutions, result in much smaller temperature files (temperature files can be tens of gigabyte in size for large problems), and are quite accurate for most weld problems. Another advantage is that the solution is mesh size independent. The mesh refinement requirements for the thermal portion of a numerical solution are stricter compared with the corresponding structural solution requirements. Hence, using CTSP one can use the mesh refinement required for the structural portion of the solution.

The final step is the structural solution with temperatures serving as loading. This requires the use of a weld specific constitutive model [3, 4]. The constitutive law must include melting/re-melting as weld metal is deposited and solidifies, material annealing to annihilate inelastic strains as material melts, large strain effects, phase transformations and transformation plasticity, and must efficiently permit the treatment of weld material that has yet to be deposited. A USER-WELD routine that interfaces with the ABAQUS software is used for this purpose. The weld specific features are implemented within a Lemaitre-Chaboche cyclic thermal plasticity theory.

The result of the sequence illustrated in Figure 1 is distortions and residual stresses. As seen, if the distortion or residual stress goals are not met, solution iterations are needed, with different weld parameters, sequences, etc. It is convenient to automate this re-analysis procedure. The entire procedure is automated (Reference [5]).

There are several assumptions, which turn out to be very good based on experience, that are made to render the solution process stable and rapid (References [3-5]). It is not necessary to perform a coupled thermo-mechanical solution, include latent heat of fusion, and creep effects in the model. For most practical problems, these issues are found to be of second order importance. Moreover, inclusion of these effects greatly increases solution time.

Weld Design Optimization

Weld design is important in controlling welding-induced distortion in large, complex structures. The general principle of placing a weld is to make it close to the neutral axial of the structure. This will induce less bending and twisting distortion. But in a complex structure, the problem is far more complicated.

Distortion Control. Figure 2 is a component in an earth-moving vehicle. It serves as an example to illustrate how the 7-pass V-groove affects the global distortion of the component. From the local viewpoint, this 7-pass V-groove weld should be designed as a double V with a 3-pass weld inside and a 4-pass weld outside. In doing so the welding of V-groove will produce minimum distortion, but it will not help to reduce the global distortion. Two other possibilities are welding all 7-passes from outside or welding all 7-

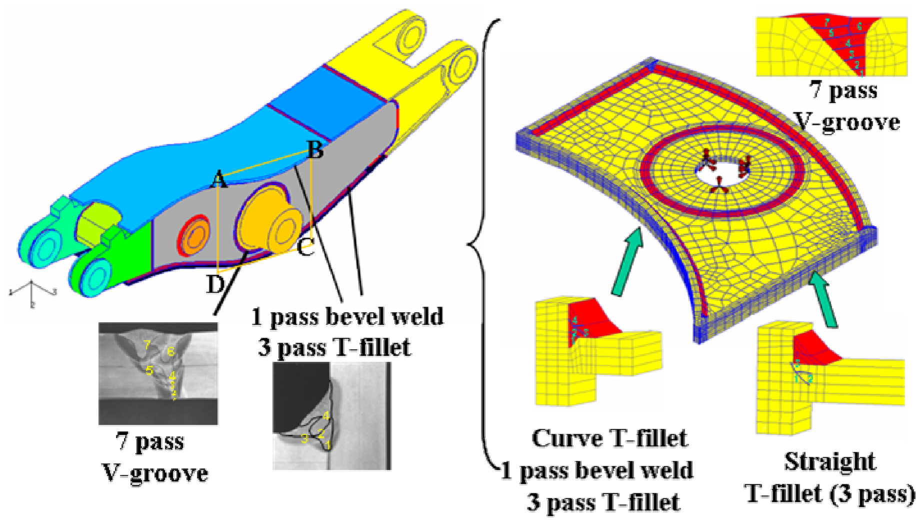

Figure 2. Component of Large, Complex Structure

passes from the inside. The computational procedure discussed below was used to answer the question of which method produces the smallest distortions.

For simplicity, a relatively small piece was cut from the component to study the 7-pass weld effect on global distortion. This piece is still two by two meters in size. The cutting line is AB, BC, CD and DA as shown in Figure 2. The finite element model of this piece is shown in Figure 2 (right hand side), which consists of the 7-pass circular V-groove weld (of the center circular piece), two curved T-fillet welds with 1 pass bevel welds and 3 pass T-fillet welds and two straight T-fillet welds with 3 passes. The welding sequence consisted of welding the circular V-groove first, and then the T-fillet welds.

By performing computational weld modeling, the distortion histories at the four corners of the model were obtained experimentally. For verification of the model predictions, the welding experiment was conducted by using laser sensors (LS -3, -4, -7, -8 in Figure 3) to monitor distortion at the corners of the part. Excellent comparison between prediction and experiment was observed (see Reference 6).

To illustrate the predictive power of computational weld models consider the following sequence study. Figure 3 shows that different distortion results were obtained between welding the V-groove from topside (outside in the component) and bottom side (inside in the component). When welding the V-groove from bottom side, the final distortion is much smaller than that of welding from topside. Moreover, as can be seen from Figure 3, the distortion is much more uniform with the new design compared with the original. This is because the counterbalance between distortion of the V-groove and distortion of T-fillet. It is clearly shown in Figure 3 that negative distortion is obtained

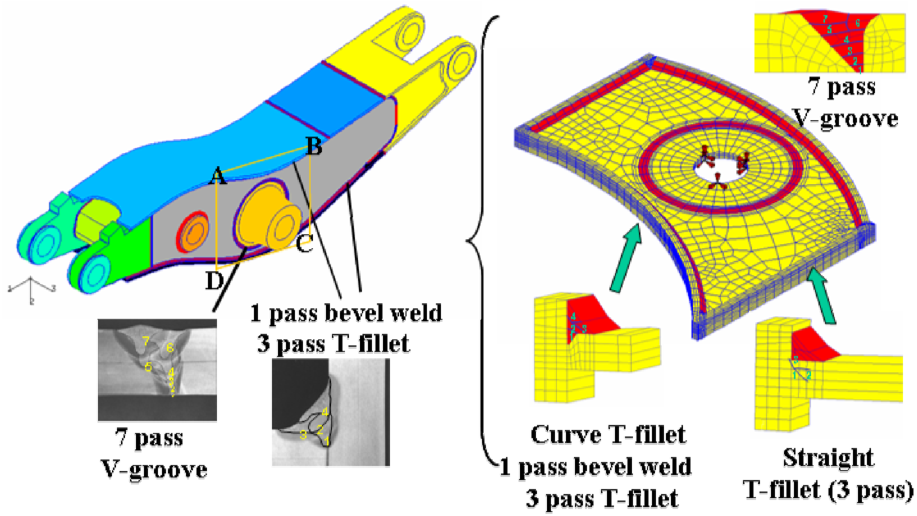

Figure 2. Component of Large, Complex Structure

after welding the V-groove and negative distortion values tends to become smaller when welding T-fillet.

Therefore, welding the 7-pass V-groove from inside the component (bottom side) was driven from the finite element analysis results. But from practical view of point, welding from inside the component increases the complexity of welding operations. However, distortion control was more important for this component and this sequence has been adopted in the plant.

Residual Stress Control. The example illustrated above shows the usefulness of distortion control using computational weld modeling. These techniques have been implemented into the fabrication designs for this and numerous other fabrications (see Reference [3] and the references therein). There are a number of ways to modify the welding process to either control distortions or to manage residual stresses. These include weld sequence definition, pre-cambering, pre-bending, heat sink welding, thermal stretch welding, heat input control, weld torch travel speed, among many others. The present example illustrates how a service-cracking problem was eliminated by a simple weld sequence change that was determined via computational weld analyses.

Consider a swivel frame in a large off road mining vehicle as in Figure 4. The finite element mesh to the left represents an axis-symmetric model of a cylinder welded to a base plate via a Tee-fillet weld. Field cracking was observed in the vehicle, and it sometimes occurred immediately after the weld. The cylinder is quite large with a diameter of 3.5 meters and a thickness of 33 mm while the base plate has a thickness of 100 mm. The original weld sequence is illustrated in the top of Figure 4 and labeled sequential. This led to the type of cracking illustrated in the inset, where the cracks

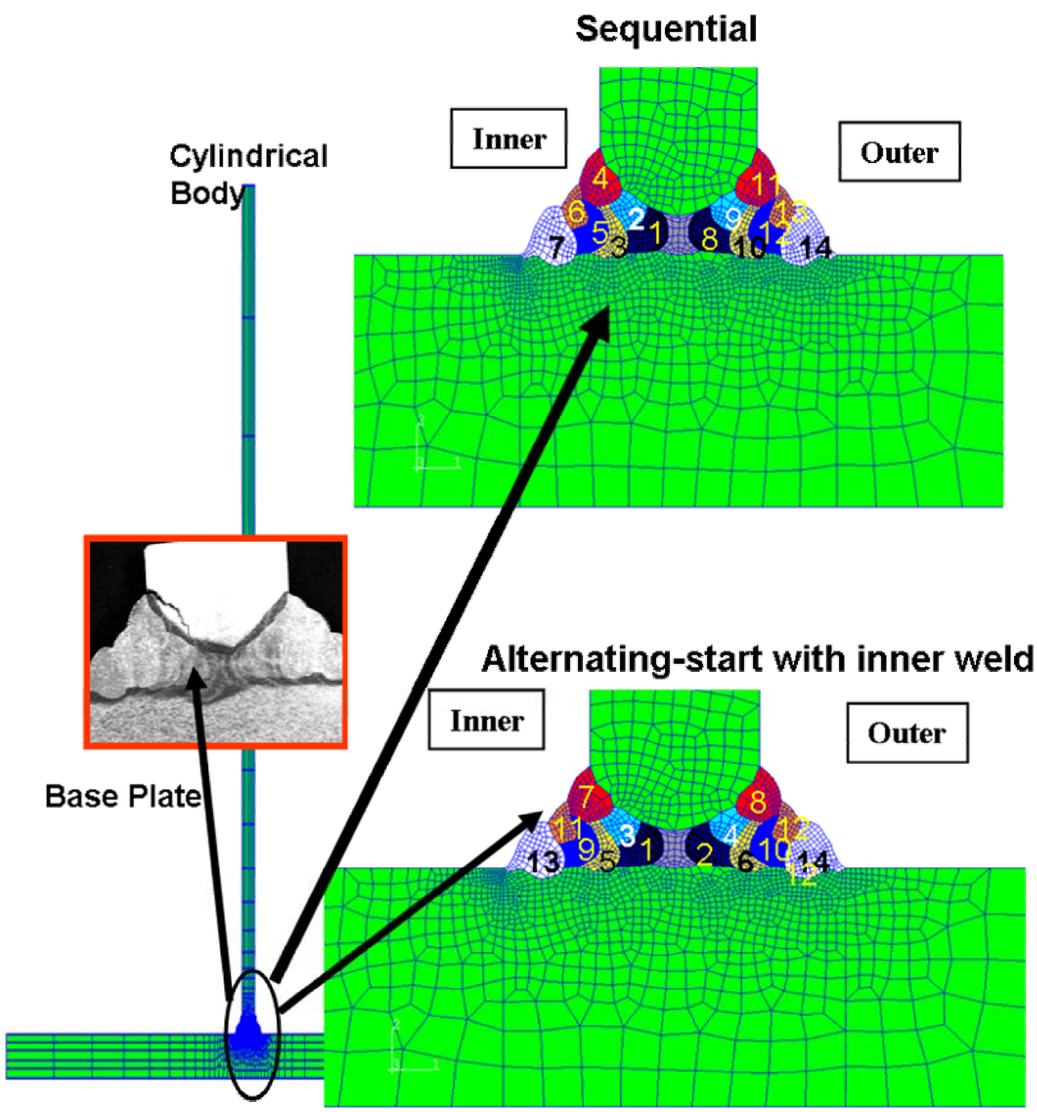

Figure 4 – Car body Weld Sequence Example.

initiated in the cylinder at the inner diameter, near the toe of the weld, through the cylinder.

Since the thickness of the welded part is large, it was postulated that constraint was a possible cause of the cracking. As such, the VFT code was exercised in an attempt to develop a weld sequence that might eliminate the problem. After several iterations, the sequence illustrated in the bottom portion of Figure 4, labeled alternating was determined to minimize both the constraint and the weld residual stress state. This sequence consists of welding at the inside diameter first, followed by the outer diameter, then inner diameter, outer diameter, etc., until the weld is complete. The residual stress state that develops from the two sequences is illustrated in Figure 5. Here it is seen that the stresses near the toe of the weld are markedly higher with the original sequence compared with the sequential sequence. In addition, though not shown here, the constraint for the alternating weld was also significantly lower than the sequential weld. This new sequence was implemented into the shop floor of the manufacturer and not one failure has been observed since. This is an example that illustrates how clever design and control of fabrication induced residual stresses can eliminate field failures.

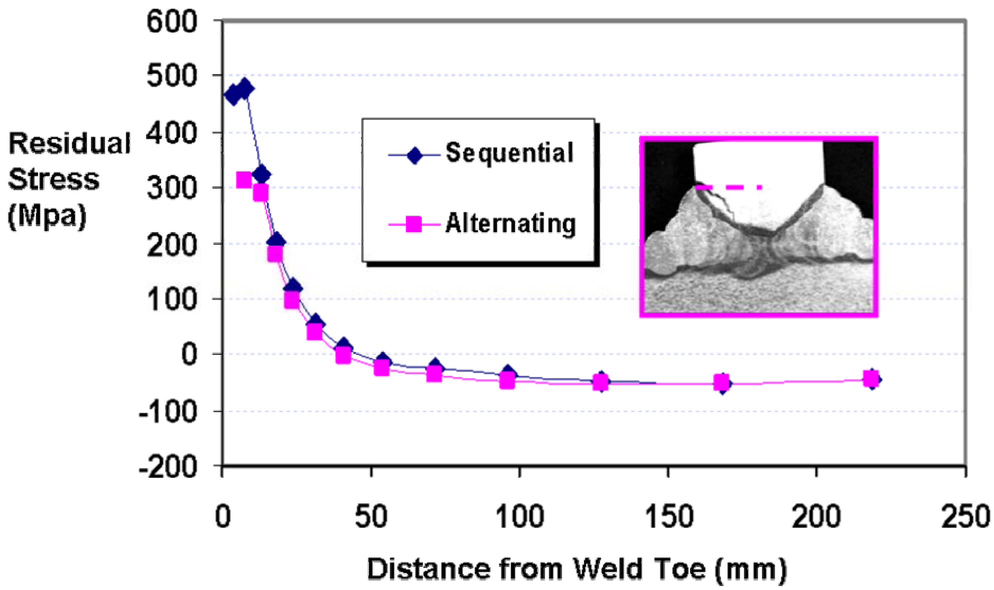

Figure 5 – Residual Stresses From Sequential and Alternating Welding.

Conclusions

Computational weld modeling has emerged as a practical technique in industry to save costs and improve service performance. The authors have been involved in about thirty such solutions to date for many different components with remarkable results. Please see the references for more examples.

References

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