Computational Weld Mechanics:
Is Real-Time CWM Feasible?
Recent Progress in CWM

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Introduction

The first part of the paper discusses the feasibility of real-time CWM. We define what we mean by real-time CWM, discuss the current speed of CWM and predict the speedups likely to be achieved in the next two to five years. Finally, we discuss the implications of real-time CWM on welding engineering and welding research.

The second part of the paper discusses some recent progress in CWM; the use of composite meshes, some of their advantages and limitations and a software framework that is intended to be used for CWM of welded structures containing many long, multipass welds.

Real-Time Computational Weld Mechanics

What Is Real-Time CWM

There is a widespread perception in the welding research community that 3D transient CWM is too expensive to be practical. Indeed many if not most CWM analyses published to date use either plane strain or shell assumptions to reduce the problem to 2D. For the question , “Is real-time Computational Weld Mechanics (CWM) feasible?” to have meaning, it is necessary to first specify what we mean by a solution and what errors in the solution are tolerable. We define the solution to be the transient temperature, displacement, strain and stress and microstructure evolution evaluated at each point in space and time near a weld in a structure. In the authors' opinion, numerical errors in temperature, stress and strain in the range [5%, 10%] are acceptable. By numerical errors we mean the difference between the numerical solution and an exact solution to the mathematical problem being solved. By real errors we mean the difference between the numerical solution and experimentally measured values in which there are no experimental errors. It is difficult to reduce real errors below 1% because of errors in available data for material properties such as thermal conductivity and Young's modulus. Numerical errors in the solution that are much larger than 10% often would not be accepted. The numerical error estimates do not include errors in material properties or in microstructure evolution. We assume that errors in geometry will be held to less than the maximum of 1% or 0.5 mm except for some details such as fillets.

It is also necessary to specify a computer. In December 1999, IBM announced plans to develop a 10^{15} flop computer called Blue Jean by 2005. Since a September 1999 Pentium III 600 MHz has a computational speed of roughly 5x10^8 flops, Blue Jean promises to be 2x10^6 times faster and cost about 20,000 times more ($100M). We will restrict our discussion to standard workstations that are widely available and routinely used in industry. All performance data given will be for our current software running on a Pentium III 600 MHz with 512 MB RAM.

There is also the issue of whether multiple processors should be allowed as in parallel or distributed processing. IBM's Blue Jean computer will use one million processors using multiple threads. However, for most algorithms experience to date has shown that achieving speedups greater than 100x is relatively rare with complex codes. In many cases speedups of the order of 10x can be achieved fairly easily using multiple processors. This is likely to change in the next five to ten years as computer science research focuses on software to exploit multiple processors. For this paper, we make the pessimistic assumption that a speedup of 10x could be achieved with multiple processors.

It is also necessary to say when one predicts that real-time CWM when will become feasible. The reason is that the speed of computers increases by a factor of roughly 1.7 times each year. In the past 18 years the speed of computers has increased roughly 20,000 times. In the next 18 years the speed of computers is expected to increase at least as rapidly. Clearly even if one does nothing in CWM, someday real time CWM would become feasible simply due the increasing power of available computers.

There are also issues such as how complex is the geometry of the structure being welded? Is this is a multipass weld? Does the weld weave? Is the weld pulsed? In this paper, we only consider the simplest case, a straight single pass weld. However, we will include the complete structure being welded. It should be mentioned that the ultimate objective of CWM is to analyze the fabrication of complete structures that have many welds, often long multipass welds.

Current Performance for CWM

We begin by considering thermal-microstructure evolution of an arc weld that is a 100 mm long and made with a welding speed of 1.785 m/s. The weld is completed in 71.4 s. Of course, most production welds use much faster welding speeds. We are able to do a high resolution 3D transient thermal analysis in less than 30 min. This analysis involves 40 time steps and 8,718 8-node bricks. This thermal analysis is approximately 25 times slower than real time. The thermal stress analysis requires about 280 minutes and is about 235 times slower than real time. The thermal stress analysis is roughly 10 times slower than the thermal analysis. Both analyses use 8-node bricks. The mathematics used is described in detail in [1].

To a large extent, the time domain for the thermal-microstructure analysis in many welds can be decomposed into three stages: starting transient, steady state and stopping transient. If this were done, it would be feasible to achieve real-time thermal analysis today. The question of time integration will discussed in more detail later.

There are many reasons why thermal stress analysis of welds is a much more challenging problem than thermal-microstructure analysis. The thermal-microstructure analysis only involves material a short distance from the weld path, usually less than ten weld pool diameters. Only this relatively small region near the weld need be analyzed for temperatures and microstructure evolution. Usually, this width is less than 10 cm. In contrast, in a thermal stress analysis the complete structure being welded is in quasi-static equilibrium. Thus thermal stresses generated by the welding process travel over the complete structure. This makes it much more difficult to do the analysis in a relatively small region around the weld. In particular, it is difficult to choose realistic boundary conditions for a small region around the weld.

Another factor is that the mesh used for thermal-stress analysis must be finer than the mesh used for thermal analysis. In this paper we use an 8-node brick for stress and thermal but the stress treats the temperature in the element as piece-wise constant. The reason for this is that strain is the gradient of the displacement. The gradient operator essentially reduces the order of the strain field to one less than the order of the displacement field. If the thermal strain is to be consistent with the strain from the displacement gradient, the thermal element should be one order lower than the displacement element. Another reason that thermal stress is more challenging than thermal analysis is that thermal analysis is strictly positive definite because of the capacitance matrix. On the other hand, the quasi-static thermal stress analysis is only made positive definite by constraining rigid body modes. In addition, a temperature increment of the order of 100 K generates a thermal strain equivalent to the yield strain. While larger temperature increments do not cause serious difficulties for the thermal solver, temperature increments that generate stress increments larger than the yield strength do make it difficult to do an accurate thermal stress analysis.

If one used a 20-node brick with 60 displacement dofs for thermal stress analysis and an 8-node brick with 8 temperature dofs for thermal analysis, the thermal stress analysis would have 60/8 = 7.5 times more equations to solve. For a regular mesh topology, each global equation has 243 nonzero terms compared to 27 nonzero terms for the thermal solver. Thus a very rough lower bound estimate is that such a thermal stress solver is (60/8)(243/27) = 67.5 times more expensive than a thermal solver. It also requires more than 70 times as much memory because stress and internal variables must be stored at Gauss points. These rough estimates agree with our experience that the thermal stress analysis in CWM is roughly 10 times more expensive than the thermal-microstructure analysis when 8-node bricks are used for both analyses. We would expect the stress analysis to be roughly 100 times more expensive if 20-node bricks were used for stress analysis and 8-node bricks for thermal analysis.

The cost of CWM is roughly linearly proportional to the number of elements in the mesh, the number of time steps, the number of nonlinear iterations per time step and the time required for each nonlinear iteration. There are opportunities to optimize the mesh and reduce the number of elements. In particular, the use of shell elements could dramatically reduce the number of the elements in a mesh. However, near the weld the solutions is truly 3D and shell elements could introduce large errors. We have long favored the use of local 3D transient analysis near the weld pool and shell elements farther from the weld pool where the assumptions of shell theory are valid. There are also opportunities to take longer time steps. A steady state Eulerian analysis of an infinitely long weld in a prismatic geometry would only require one solution step which would require approximately one minute CPU time for thermal analysis and 20 minutes for a thermal stress analysis This could easily be done in real time for a sufficiently long weld but would not capture the transients on starting and stopping the weld. Solver improvements are expected to provide a three-fold reduction in the number of nonlinear iterations. If shell elements reduced the number of elements by a factor of ten, time steps were ten times longer, solvers were three times more efficient, non-solver code was made three times as fast and multiple processors provided a speedup of ten, the total speedup would be 3000 times. This would be 13 times faster than real-time for this weld and faster than real time for many, perhaps most, production welds. It is our opinion and of course it is only an opinion that these speedups can be achieved in the next three to five years. This ignores any increases in speed in computers such as the Intel Itanium or Merced chip that is due to be released in the year 2000 and which promises to be substantially faster than Pentium chips.

Implications of Real-Time CWM

If our prediction that CWM can be done in real-time is correct then CWM is likely to be used routinely in industry. This raises the question of what will be the impact of routine use of CWM in industry. We believe this will dramatically change both engineering and research in the three main components of welding technology; materials engineering, structural engineering and weld process development for all types of welded structures. We expect the changes to research to be particularly dramatic.

Materials engineering will be able to simulate microstructure evolution much more accurately. While research on the evolution of microstructures is already well advanced, research on the difficult issue of predicting or estimating material properties for a given microstructure with particular emphasis on failure mechanisms is only beginning. The other hard materials research issues will involve local bifurcations such as nucleation of phases, shear bands and porosity. (What materials engineers call nucleation, mathematicians call a bifurcation.) These are the three fundamental bifurcations in material engineering. Shear bands involve only deviatoric stress and strain. Porosity involves only volumetric stress and strain. The computational mechanics of these bifurcations is a fairly hard research issue that to date has been almost totally ignored in the welding literature. It will become a major focus of research in materials engineering for welding.

Structural engineering for welded structures will focus on the life cycle of welded structures from conceptual design, to manufacture, in-service use, maintenance and decommissioning. While life cycle engineering of welded structures is not novel, CWM is usually ignored. For example, while the role of residual stresses in welded structures has long been recognized, it has seldom been included in structural analysis. We believe that CWM will enable the effects of residual stress and weld microstructure to be integrated into the life-cycle engineering process. More research will focus on buckling of welded structures. The hardest CWM research issues in structural engineering will be local failure modes due to shear band or porosity formation. We expect CWM to become an integral part of structural engineering of welded structures.

The third component of welding technology will be weld process development. The focus will be on weld pool, arc and laser physics. This involves the hardest research issue of all - turbulence. Turbulence, which is a major factor in making weather forecasting difficult, is a chaotic phenomenon. This implies that the CWM of weld processes will be closely tied to experiments for some years. CWM of weld processes is likely to be strive to resolve essentially small process variations and short time behavior. We are particularly impressed with the weld pool models developed under the leadership of W. Sudnik [2] who has developed weld pool models that avoid the turbulence problem by dealing with average or roughly mean-field values.

Perhaps the most important change arising from the routine use of CWM in industry is that CWM will become closely tied to experiments, including experiments on real production structures. In the past, it has been too expensive to do experiments to validate CWM. If CWM is used by industry, in a sense the experiments become free. This will lead to tight coupling between experimental data and CWM analysis. This in turn will allow both experiments and CWM to be highly optimized and validated. When this stage is reached, then CWM will have become a mature technology.

Some Examples of Recent Progress in CWM

Composite Meshes

Figure 1 shows a composite mesh for a weld on a pressure vessel. These meshes do not always conform; i.e., nodes and element faces on either side of the interface need not match. Continuity of temperature or displacement fields across the interface is maintained by constraints. These constraints are imposed automatically by the code. Composite meshes make it much easier to mesh complex structures because each part of the structure can be meshed independently and the mesher is not required to maintain continuity of the mesh.

In Figure 2, composite meshes are being used as a form of adaptive meshing. Somewhat similar efficiencies could be achieved by adaptive meshing. Composite meshes are similar to adaptive meshes in that both are based on constraints, i.e., some nodes are declared to be linearly dependent on other nodes. Composite meshes differ from adaptive meshes in that fine elements need not be children of coarse elements, i.e., fine elements need not be formed by refining coarse elements. In some cases, this can greatly reduce the work needed to mesh a structure for CWM.

Table 1. Composition of HSLA steel.

C	Ni	Si	V	Mo	W	Mn	Cr	Cu	P	Al
0.12	0.11	0.16	0.001	0.001	0.001	0.91	0.01	0.001	0.002	0.04

The weld pool dimensions for a double ellipsoid weld pool model were: Front ellipsoid width, depth and length in meters are (0.006, 0.000914, 0.006). Rear ellipsoid width, depth and length are (0.006, 0.000914, and 0.012).

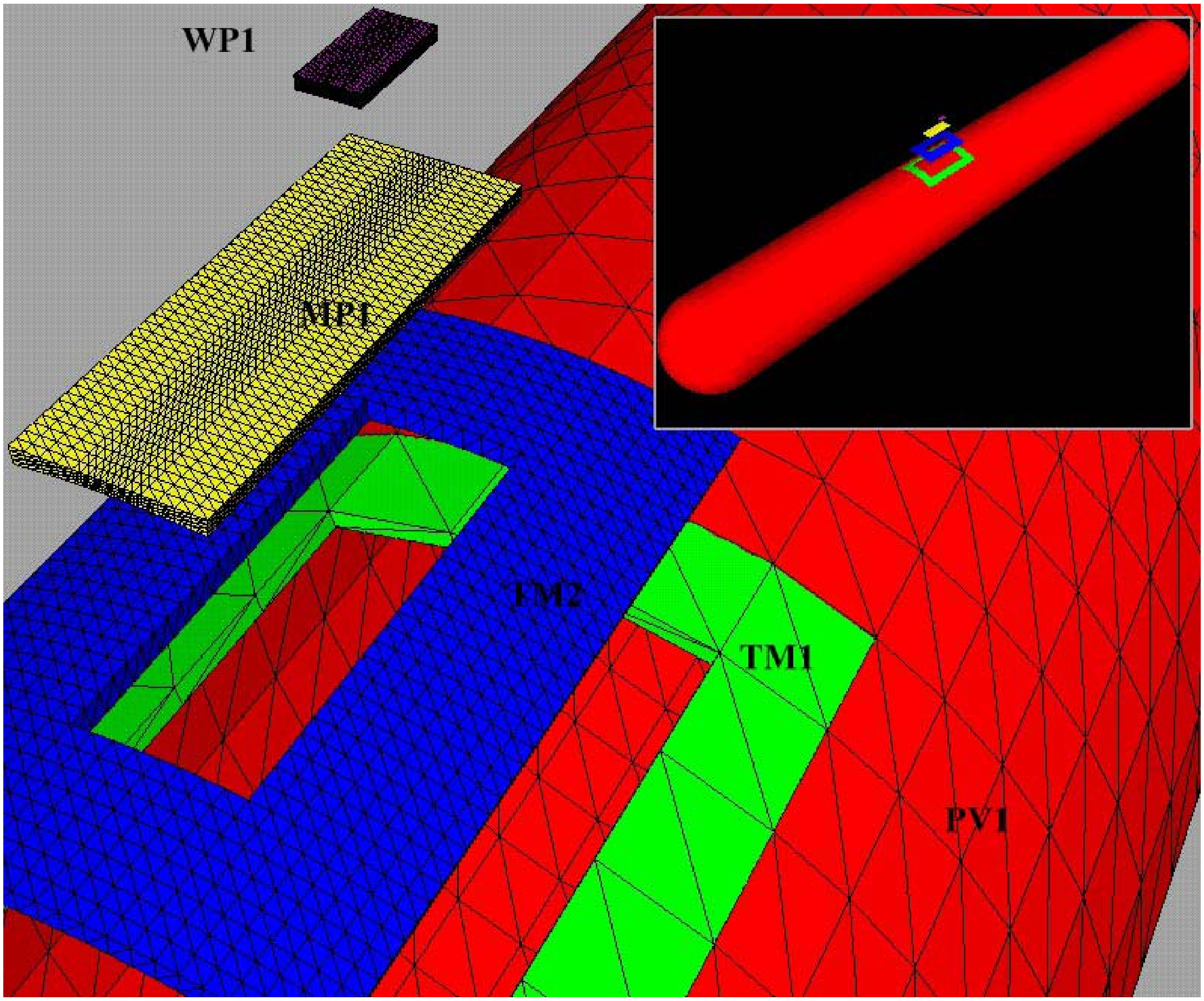

Figure 1 shows a composite mesh for a weld on a pressure vessel. The mesh for the vessel consists of five different mesh parts. The mesh for the pressure vessel, called PV1, had 3006 8-node brick elements. For each weld, a fine mesh with 3456 elements, called MP1, was created for the region around the machined slot. Outside of MP1, a transition mesh with 768 elements, called TM2, and coarser transition mesh called TM1 with 140 elements was made. Inside MP1 an even finer mesh was created, called WP1, with 3840 elements. The mesh WP1 was moved with the arc during the welding process.

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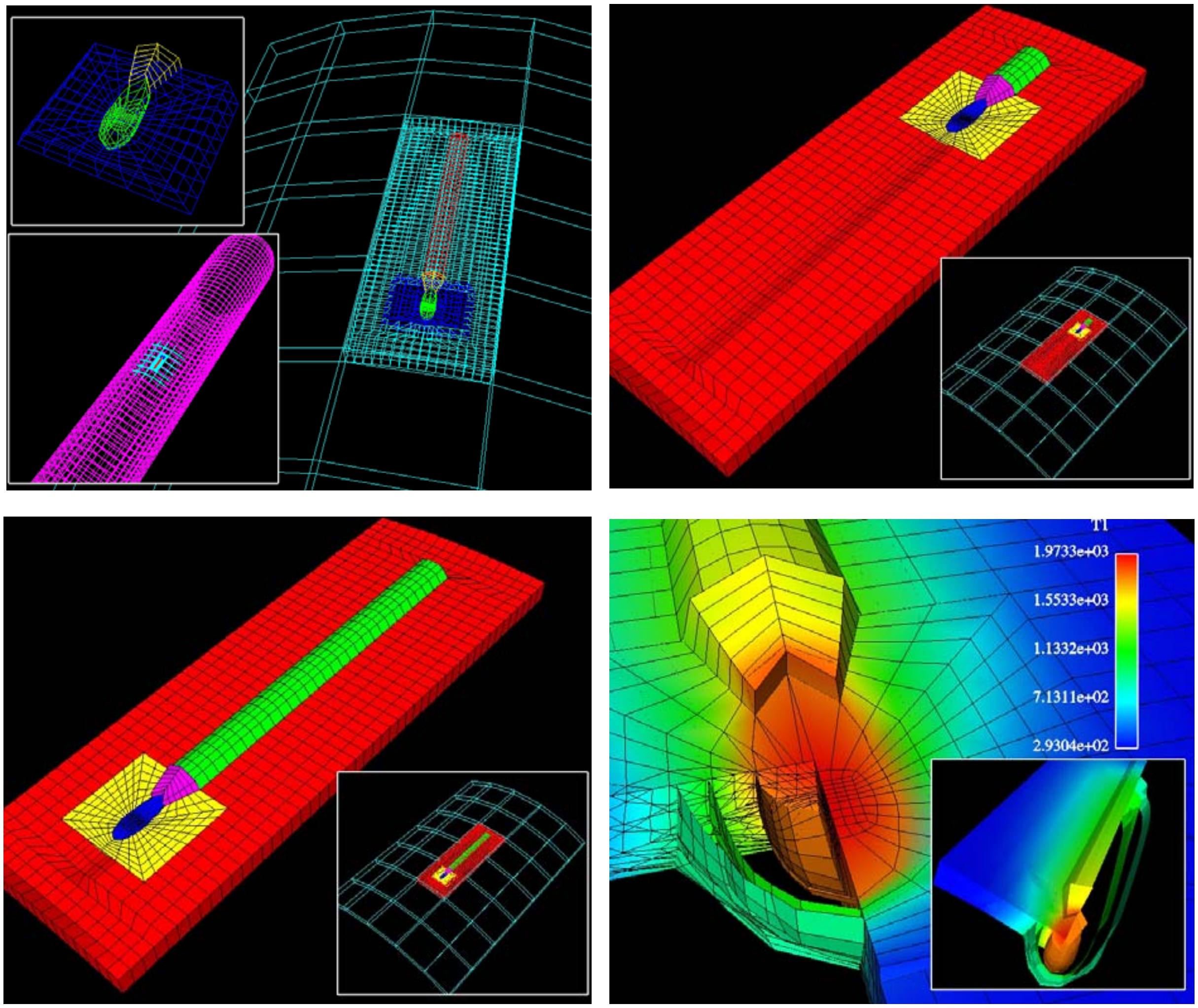

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Figure 2. Upper left shows a composite mesh. Upper right and lower left show the moving mesh near the weld pool region with the weld and filler metal being added. The lower right figure shows the temperature near the weld pool.

Figure 2 shows an example of the weld pool being meshed with element boundaries on the liquid/metal interface. This weld pool mesh is parameterized so that weld pool shape can be defined dynamically during the analysis. We call this a parametric conforming weld pool mesh. Note that in Figure 2 lower right, the temperature varies linearly through the thickness of the wall except very close to the weld pool. This implies that only 2 nodes through the wall are needed to accurately capture the temperature variation. The five nodes that we have used were not necessary and a significant reduction in computing time could have been achieved by using elements that were linear through the thickness of the wall and preferably quadratic or cubic on the wall surfaces.

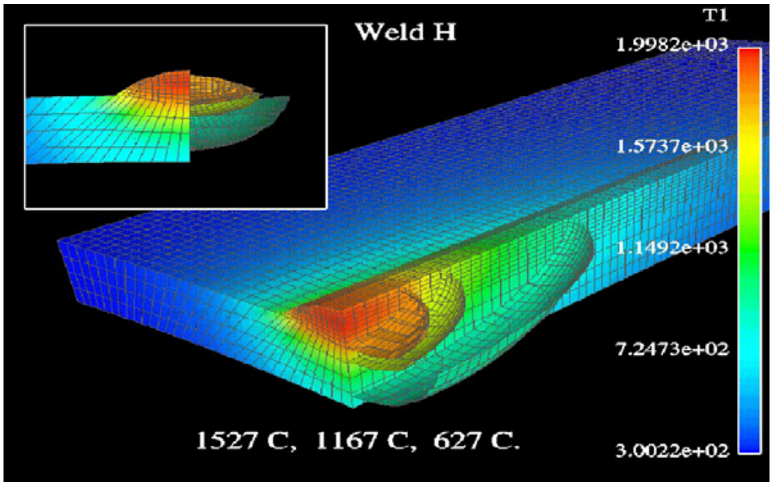

Figure 3 shows the temperature distribution in a composite mesh with fewer mesh parts. In this case there is no mesh part WP1. Thus the mesh makes no attempt to capture the weld pool geometry by placing element boundaries on the weld pool boundary. We call this a nonconforming weld pool mesh.

Figure 4 shows the thermal flux vectors on the weld pool boundary.

Figure 5 shows displacement vectors near weld pool.

Figure 6 shows the stress ellipsoids near the weld pool. The axes of each ellipsoid are the principal stress vectors.

Discussion of Progress in CWM

We learned two important lessons from our experience with parametric conforming weld pool meshes. First and perhaps most important, the distorted elements in conforming weld pool meshes appear to have far larger discretization errors than the nonconforming weld pool mesh. This should not have been surprising because the effect of element distortion on accuracy has been studied and is reasonably well understood [3, 4].

The second important lesson that we learned was the need to balance the overhead of working with optimized meshes with the cost of solving. Although the cost of solving the nonconforming mesh is slightly higher, the cost of overhead is less and in this case the total cost was lower.

CWM of Welded Structures

In pursuing our ultimate objective of CWM analyses of welded structures that have many, multipass welds, we have developed a software environment that separates the structural design, weld joint design and production welding stages. Structural design specifies the parts to be welded, in particular their geometry, their material types and any relevant internal variables and boundary conditions needed constrain rigid body motion. Weld joint design specifies a curvilinear coordinate system for each weld joint. Each weld pass on each weld joint has a start point, end point and a start time. Production welding specifies the welding procedure for each weld joint. The welding procedure defines the welding parameters for each pass, e.g., current, voltage, speed, weld pool size, shape and position in a cross-section of the weld joint. These three data sets fully define the process of welding a structure and has the data needed perform a computational weld mechanics analysis for fabrication of a complete structure.

Figure 7a shows the two parts of a tee joint to be welded. Figure 7b shows a possible weld procedure with 12 weld passes. Figure 7c shows the multiple passes generated by the weld procedure.

References

1. J. Goldak, V. Breiguine, N. Dai, E. Hughes, and J. Zhou, Thermal Stress Analysis Near the Weld Pool, Mathematical Modelling of Weld Phenomena 3, Ed. H. Cerjak, The Institute of Metals, pp. 543-570, 1997.

2. W. Sudnik, Mathematical Modelling of Weld Phenomena 3

3. O.C. Zienkiewicz and R. L. Taylor, The Finite element Method, Fourth Edition, page 170, Volume 1, McGraw-Hill, 1988.

4. E. Wachpress, High Order Curved Finite Elements, Int. J. Num. Meth. Eng. 17, pp. 735-745, 1981.