Optimization of a Weld Overlay on a Plate Structure

An overlay weld repair procedure on a 1066.8 × 1066.8 mm² square plate 25.4 mm thick was simulated to compute the 3D transient temperature, microstructure, strain, stress, and displacement of the overlay weld repair procedure. The application for the overlay was the repair of cavitation erosion damage on a large Francis turbine used in a hydro-electric project. The overlay weld consisted of a 4 × 6 pattern of 100 × 100 mm² squares. Each square was covered by 15 weld passes. Each weld pass was 100 mm long. The total length of weld in the six squares was 36 m. The welds in each square were oriented either front-to-back or left-to-right. The welding process was shielded metal arc. The analysts shows that alternating the welding direction in each square produces the least distortion. A delay time of 950 s between the end of one weld pass and the start of the next weld pass was imposed to meet the requirement of a maximum interpass temperature to 50 °C.

DOI: 10.1115/1.4000511

1 Introduction

Cavitation erosion damage on hydraulic turbine blades is repaired by overlay welding. It is desirable to manage the distortion caused by overlay welding so that the hydraulic efficiency of the turbine is not reduced.

In 1987, Chakravarti et al. [1] described an analysis to predict the distortion in a plate due to an overlay repair weld; see Fig. 1. The associated experiments were designed to simulate the overlay weld repair of a blade of a large Francis hydraulic turbine.

Their low alloy A36 steel plate was 19 mm thick and 305 × 457 mm². Three edges were stiffened with welding gussets, as shown in Fig. 1. After welding the gussets, the assembly was heated to 650 °C to relieve residual stresses. A rectangular cavity 610 mm long, 406 mm wide, 3.2 mm deep was machined to simulate the layer of metal that was damaged by cavitation, and hence, removed. This cavity was later filled by the overlay repair weld.

Chakravarti et al. [1] did three experiments and three computer simulations for three different patterns of the 2 × 3 overlay squares. Each square was 100 × 100 mm². They did each of three computer simulations by an ingeneous sequence of analyses. The first analysis stage that they did was a 2D Lagrangian thermal analysis with filler metal added in each time step. Their low alloy steel welds were assigned the above initial stress. Each block was rotated to its initial stress to determine the residual stress and distortion in the structure as it is being welded. There is some explanation in the following sections.

From this 3D transient stress analysis of one weld pass in one square, they did their third analysis stage that took the increment in initial stress from the first pass and applied it to the weld pass on either side of the first pass. They then applied that increment in initial stress to the remaining pairs of weld passes in that square.

For the fourth analysis stage, they did an equilibrium analysis of a single block with that initial stress to determine the residual stress and distortion in that square.

In their fifth analysis stage, they assembled the 2 × 3 patterns of 100 × 100 mm² squares in which the block for each square was assigned the above initial stress. Each block was rotated to its appropriate orientation for that pattern. They did not include the gussets in their analyses. Each 2 × 3 pattern of blocks was then assembled into the finite element (FEM) mesh of the full plate. For the sixth stage, they did an equilibrium analysis with that initial stress to compute the residual stress and distortion in the full plate with the 2 × 3 pattern of 100 × 100 mm² squares for each of their three patterns of overlay weld orientation.

These analyses were performed for three patterns of blocks. The left-to-right pattern did all welds running from left-to-right in Fig. 1. The front-to-back pattern did all welds running from the front of the plate to the back of the plate shown in Fig. 1. The check board pattern alternated front-to-back and left-to-right blocks. Note that their analyses did not permit sequencing the welding of the blocks.

The computed distortion in these three patterns was compared with the distortion in experimental overlay welds. The predicted distortion was qualitatively similar to the distortion measured in the matching experiments.

2 Analysis Methodology

Analyses reported in that paper are done by a software called VRWeld. The development of VRWeld was lead by Goldak [2]. Given the computer aided design (CAD) files for the geometry of the parts to be welded, the set of weld procedures to be used, the weld joint paths, and material properties for the materials being welded, VRWeld enables a designer to simulate the transient 3D temperature field, the evolution of microstructure in low alloy steel welds [3,4], and, transient 3D displacement, stress, and strain in the structure as it is being welded. There is some explanation for each analysis in the following sections.

2.1 Problem Geometry, FEM Mesh and Material Composition. The analyses reported in this paper have many similarities to the problem reported in Refs. [1,5,6,8]. Their low alloy steel plate was 19 mm thick and 305 × 457 mm². Three edges were stiffened with welding gussets, as shown in Fig. 1. A rectangular cavity 610 mm long, 406 mm wide, and 3.2 mm deep was machined to simulate the layer of metal that was damaged by cavitation, and hence, removed. This cavity was to be filled by the overlay repair weld.

In this paper, although the experiment was intended to be the same as the problem described in Ref. [1], the methodology for the simulation analysis was quite different. In this paper, the analysis attempted to capture a useful approximation of most of the relevant 3D transient physics accurately, except for the physics within the weld pool. The thermal analysis was a 3D transient Lagrange thermal analysis with filler metal added in each time...
step. The evolution of the 3D transient microstructure in the heat affected zone (HAZ) and fusion zone was simulated. A 3D transient thermoviscoelastoplastic stress analysis was performed.

The mesh was a mixture of 8-node bricks and 6-node prisms with 1150 elements in the block for each 100 mm square. The mesh of each filler metal weld pass contained several 8-node brick and 6-node prism elements. A cross section of the mesh is shown in Fig. 2. The FEM mesh for the complete structure contained 32,058 elements and 53,618 nodes. The mesh for the plate and stiffeners is shown in Figs. 2–4.

In this paper, some ideas on overlay welds from Paradowska et al. [7] were used. In particular, their requirement that the weld interpass temperature did not exceed 50°C was accepted. Also, their alloy composition for base metal and filler metal and their weld procedure parameters of weld speed 6 mm/s, 30 V, 290 A, and 0.85 efficiency factor were accepted.

2.2 Transient Thermal Analysis. The 3D transient temperature is computed by solving the transient heat equation

$$\dot{h} + \nabla \cdot (-\kappa \nabla T) + Q = 0$$

where \(h\) is the specific enthalpy, the super imposed dot denotes the derivative wrt to time, \(\kappa\) is the thermal conductivity, \(T\) is the temperature, and \(Q\) is the power per unit volume or the power density distribution. The transient heat equation is solved with a Lagrangian finite element method.

Each time step advanced the weld pool with a distance of 10 mm. The heating effect of the arc and weld pool was approximated with a double ellipsoid weld heat source model [9] with front axis of 6.5 mm, width axis of 6.5 mm, depth axis of 6 mm, and rear axis of 13.82 mm. The weld pool covered two elements along the length of the weld joint (6.5 mm + 13.82 mm = 20.32 mm) with two time steps per weld pool length.

The welding required 3600 time steps. However, in order to maintain an interpass temperature of 50°C, a delay of 950 s was imposed between the end of one weld pass and the start of the next weld pass. This delay time increases the welding time from 16.9 s to 967 s per weld pass. It also approximately doubles the number of time steps to 6849 and doubles the CPU time for the analysis. The welding time per weld pass times 15 passes on one 100 mm block with 950 s delay per weld pass gives a total of 14,504 s of welding time per block or over 4 h. The total welding time included cool down for 1,000,000 s (27.8 h or 11.56 days). The CPU time for the analysis was 69.8 h.

2.3 Transient Microstructure Evolution Analysis. Having to compute for the transient temperature, the evolution of the microstructure was solved using algorithms described in Refs. [3,4]. These algorithms extend the theory in Ref. [10]. The essential idea is that a pseudo-binary iron-carbon phase diagram, in which all lines and points are functions of the alloy composition, is used to estimate the equilibrium microstructure of the alloy at any time and temperature. Then the kinetics of the transformation of the austenite or gamma phase to ferrite, pearlite, and/or bainite phases that tries to drive the microstructure toward an equilibrium state is governed by ordinary differential equations such as Eq. (2). The transformation of austenite or gamma phase to martensite is governed by the Koistinen–Marburger equation, which is an algebraic equation [3].
that \( X \) is the fraction of equilibrium ferrite, not the fraction of volume that is ferrite. Also note that \( G \) is the ASTM grain size index. If \( N \) is the number of grains in 0.01 in.\(^2\), then \( G \) is computed from the equation \( N = 2^G \). Special starting procedures are required to start the integration of this ODE from \( X = 0 \). \( R \) is the gas constant.

The composition of the steel was assumed to be given in Table 1. In each time step, the microstructure evolves as it is heated into the austenite region and if the peak temperature is high enough, it transforms to delta ferrite and melts. In the austenite region, grain growth is governed by an ODE. On cooling, the austenite can transform to primary ferrite, pearlite, bainite, and/or, finally, martensite. The decomposition of austenite is modeled by an ODE that is a function of the supercooling, the density of nuclei as estimated by the austenite grain size, and the composition. In particular, the drag on the diffusion of carbon due to carbide forming elements such as Cr, Mo, and V is included. See Refs. [3,4] for details on the algorithms for the evolution of microstructure in low alloy steel welds. See Ref. [10] for additional background on the phase transformation theory.

Figure 7 shows the phase fraction of martensite at the end of cool down, and Fig. 8 shows the phase fraction ferrite at the end of cool down. The hardness computed for points that transform to austenite is shown in Fig. 9. See Ref. [4] for details on the algorithm for computing hardness in weld metal.

### 2.4 Transient Thermoviscoelastoplastic Stress Analysis

The stress analysis in VrWeld uses a Lagrangian formulation to solve the conservation of momentum and mass with a thermoviscoelastoplastic stress-strain model, based on the theory developed by Simo [11]. In each time step, the external and internal nodal forces are brought into balance using a Newton–Raphson algorithm. In each time step at each Gauss point, the increment in specific volume due to the change in temperature in a phase or due to a change in phase is applied as an initial strain. In each time step, each Gauss point is assigned a phase, based on a probability measure computed from the microstructure evolution algorithm.

Each phase has its own constitutive model including yield stress, Young’s modulus, Poisson’s ratio, hardening modulus and coefficient of thermal expansion, and its own internal variables. The material properties for each microstructure were taken from Refs. [13–15]. Rigid body modes were constrained in the stress analysis by selecting three nodes. At one node with coordinates \((x_1, y_1, z_1)\), the \(x\), \(y\), and \(z\) DOFs were constrained to zero. At a second node with coordinates \((x_2, y_2, z_2)\), the \(y\) and \(z\) DOFs were constrained to zero. At a third node with coordinates \((x_2, y_2, z_2)\), the \(y\) DOF was constrained to zero.

Figures 10 and 11 show the \(\varepsilon_{yy}\) strain at a virtual thermocouple located at the centroid of the bottom surface of the plate. The oscillations due to the thermal stress from each weld pass can be seen. Figure 10 is shown for the front-to-back pattern and for the period from 30,000 s to 70,000 s. Each oscillation is associated with one weld pass. Figure 11 also shows a longer period from 0 s to 350,000 s. In this time scale, the variation in strain for each weld pass is not resolved, which results in the thickened curve.

Figures 12–14 show distortion after cool down to 1,000,000 s for each of the three patterns. Figures 15–17 show the differences in distortion between the three patterns, i.e., the displacement in one pattern minus the displacement in another pattern.

### Table 1 Chemical composition of parent metal and weld metal materials (in wt %)

<table>
<thead>
<tr>
<th>Composition</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>Ti</th>
<th>Co</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent metal</td>
<td>0.12</td>
<td>0.63</td>
<td>0.13</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Weld metal</td>
<td>0.10</td>
<td>1.76</td>
<td>0.68</td>
<td>0.02</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Journal of Pressure Vessel Technology
FEBRUARY 2010, Vol. 132 / 011402-3

---

[Fig. 5](#) The temperature in K at a virtual thermocouple located at the centroid of the bottom of the plate is plotted versus time. Each peak is associated with one weld pass in one block.

[Fig. 6](#) The decay of the maximum temperature in the structure between two weld passes is shown as a function of time for a maximum interpass temperature of 50 °C. The delay time for any higher maximum interpass temperature can be read from the graph.
3 Discussion

Very little experimental data was available from Ref. [1] to compare with the results predicted by this FEM analysis. However, more experimental data was available from a recent experiment and analysis of a similar overlay weld repair that was instrumented with thermocouples and strain gauges [12]. Figure 18 shows the temperature at the point at which a thermocouple is located and plotted versus time. The measured temperature is shown in red, and computed temperatures are shown in green and blue. The difference in the Z572 and Z568 curves is that the Z coordinate of the virtual thermocouple was shifted 4 mm. Figure 19 shows the $e_{zz}$ strain as a function of time for strain gauge 1 on the top surface of the 100 X 100. The green curve is the strain data for the strain gauge, and the red curve is for strain data at the location and orientation of the strain gauge computed by VRWELD.

This figure shows the agreement between temperatures measured with a thermocouple and two temperatures computed by VRWELD. Note that the temperatures are in Kelvin [12]. The two virtual thermocouples are shifted 4 mm to show the sensitivity of the peak temperature to an error in positioning the real and virtual thermocouples with respect to the weld position.

Figure 19 shows the agreement in the $e_{zz}$ strain component measured by a real strain gauge and computed by VRWELD for a virtual strain gauge at that same position and orientation as the real strain gauge [12].

In viewing these two figures, it is important to note that no adjustment was made to the values of any parameters in the VRWELD analysis, except for reducing the value of the convection coefficient to account for the insulating effect of a blanket used to maintain preheat temperature. The welding process was also...
shielded metal arc (SMAW) with all of the variations typical of manual welding. These two figures give one some confidence that the analysis by VRWELD is a useful approximation of the real overlay weld repair procedure.

Figure 6 shows the temperature versus time during cool down to 50°C for a typical weld pass. If a higher cool down temperature was permitted, then the delay time for that higher cool down temperature could be read from the curve in Fig. 13. For example, a maximum interpass temperature of 100°C would reduce the delay time from 950 s to 150 s.

The equation for interpolation, based on fitting a nonlinear function to the last 4 points of Fig. 6, i.e., ((3271.310, 375.590), (3403.876, 351.693), (3643.194, 336.363), (4074.666, 325.689)), is

\[
Y = 317.934 + 10(36.8904 - 10 \log(x))
\]

where \(x\) is the time and 3271 < \(x\) < 4074, and \(Y\) is the temperature 325 < \(Y\) < 375 in Kelvin or 52 < \(Y\) < 102 in Centigrade.

It is not clear to the authors why the authors of Ref. [7] specified the maximum interpass temperature of 50°C. If hydrogen cracking is a concern, then one would expect a minimum interpass temperature, not a maximum, to reduce the risk of martensite formation. In welding alloys such as some stainless steels that are susceptible to sigma phase formation, one wishes to minimize the time in the temperature region that the sigma phase forms. One might wish to reduce the time the HAZ spends at high temperatures to reduce austenite grain growth in order to achieve higher strength and toughness and/or reduce the risk of martensite formation. It would seem useful to specify why the maximum interpass temperature is being specified and then control more directly what one wants to control.

If there was no delay time between weld passes, the total welding time for the 36 m of weld at 6 mm/s would be 6000 s (100 min or 1.67 h). A 950 s delay time between the end of one weld pass and the start of the next weld pass allowed the interpass weld temperature to cooldown to 323 K or 50°C. This delay increased...
the welding time to 278 h or 11.56 days. Solving for thermal and stress with the 950 s for cooldown between passes doubles the CPU time required to do the analysis from 46 h to 96.5 h.

If the maximum interpass temperature must be limited, e.g., to 50°C, then welding time would be significantly reduced by welding each weld pass on a different square. For the experiments simulated in this paper, welding each pass on a different square would reduce the welding time from 967 s per weld pass to 161 s per weld pass, and still satisfy the requirement that the interpass temperature in the neighborhood of each weld pass not exceed an interpass temperature of 50°C. This would reduce the welding time from 278 h to 150 h; a sixfold increase in productivity.

If one increases the number of squares, the welding time continues to drop until one reaches 56 squares. At that number of squares, the delay time drops to zero and there is no lost time due to the delay time between weld passes.

If the maximum interpass temperature can be increased above 50°C, then the delay time between weld passes decreases exponentially. For example, for a maximum interpass weld temperature of 100°C, the delay time would be reduced to 150 s from 950 s, and welding time reduced from 278 h to 150 h.

3.1 Computing Times and Computer Requirements. The CPU time for one 100 mm weld pass was about 40 s for thermal,
4 s per time step while welding, and about the same again during cooldown. The thermal analysis CPU time was about 2.4 times slower than real time for the welding. For the welding including the delay time of 950 s, the thermal analysis was about 24 times faster than the real arc time for the welding.

For stress analysis, the CPU time for one 100 mm weld pass was about 230 s and about the same again for cooldown. The total CPU time for the stress analysis during welding was approximately 23 h and a similar amount of time for stress analysis during cool down. The stress analysis CPU time was about 14 times slower than the real time for the welding. For the welding including the delay time of 950 s, the stress analysis was about 4.2 times faster than the real time for the welding.

The thermal, microstructure and stress analysis were run in parallel, i.e., as soon as the thermal analysis finished its first time step, the microstructure analysis started its first time step. As soon as the microstructure analysis finished its first time step, the stress analysis started its first time step. All three analyses were run on one Intel Core 2 quad 2.6 GHZ machine with 8 GB RAM and two 600 GB hard drives.

The analyses reported in Ref. [1] were run an Apollo DN-3000 computer with a Motorola 68020 processor, 8 MB of RAM and a 348 MB of hard drive, and it costs more than eight times more 1984 Canadian dollars than the Intel Core 2 quad machine cost in 2008 Canadian dollars. The stress analysis that ran in 96 h with 32,058 elements, 53,618 nodes, and 12000 time steps in 2008 took several days with about 200 elements in 1987. The speed up in
computing time per element is of the order of $10^7$. Roughly half of
the speed up is due to the increase in speed of the computers. This
simplistic computation implies that the CPU time is linear with
the number of elements, which is not true, and hence, underesti-
mates the speed up.

It may also be of interest to note that while it took several
person months to prepare the input files for the 1987 analysis, it
took only about 14 person hours to prepare the input data for the
current analysis, which is a much more complex and realistic
analysis.

4 Conclusion

Transient 3D nonlinear coupled simulations that capture much
of the macroscopic physics and mechanics of an overlay weld
repair of considerable complexity are shown to be solved quickly,
easily, and economically.

If the maximum interpass temperature must be limited, e.g., to
50°C, then the welding time (and cost) would be significantly
reduced by welding each weld pass on a different square. For the
experiments simulated in this paper, the welding each pass on a
The delay time to enforce a given maximum interpass temperature increases exponentially as the maximum temperature is reduced. To maximize productivity, i.e., to minimize welding time, it is desirable to choose the highest interpass temperature allowed.

If the delay time required to satisfy a maximum weld interpass temperature is long, then welding processes that have low heat input could minimize the delay time.

References