

EXPLORING A COMPLEX WELD DESIGN SPACE USING A LARGE NUMBER OF COMPUTATIONAL WELD MECHANICS ANALYSIS, TIME EFFECTIVE



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Introduction

The physics and mechanics of welding can be separated into the physics of the arc and weld pool on the one hand and the mechanics of the solid base metal on the other hand. The coupling between the physics and mechanics of the weld pool and the solid base metal is mainly Computational Weld Mechanics' (CWM) algorithms and software that predict the behavior of welds in the welded structures.

Development of CWM started in the early 1970s for practical weld engineering and it is now maturing with a good level of reliability, including complex physics of welding, material modelling, and stress– strain dependency on temperature and evolution of microstructure. Recent activities have focused on computational strategies and how they are integrated with other approaches to facilitate the use of simulations in industrial scale engineering with sizeable geometry and real-world complexity. Available modeling packages of the welding process solve the welding process based on 3D transient nonlinear finite element analysis (FEM) with realistic 3D geometry using complex numerical algorithms and are often solved for thousands of time steps associated with the welding progress¹.

A CWM package can save time, money and explore “what if” scenarios that are difficult to assess by analytical approaches, and/or through experimentation alone. A CWM package can be viewed as a control box that has a set of output responses associated to a set of input parameters. The input parameters can be welding parameters e.g. weld power, weld speed, sequencing, etc. or parameters associated with the welded structure such as geometrical dimensions, weld location, weld size, fixturing, and more, or workmanship factors such as welding flaw, cracking, randomness, and so on.

A welding specialist can render opinion on the effect of welding factors and may use further analytical calculation to quantify some effect on simple cases. However, the complexity of existing welded structures and the level of welding engineering demanded for today's welding problem require exploring a complex weld design space using a large number of analysis where developing a consistent solution through intuition based approaches and simplified analytical calculations become unfeasible (perhaps impossible).

¹ M. A. J. A. Goldak, Computational Welding Mechanics, N. Y.: Springer, 2005.



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Even using a predictive computer model, a designer cannot make a decision based on a single analysis- reality requires solving several analyses in a short time and reasonable cost (a challenging task). This is due to complexity of a weld model that needs expert user time and requires long CPU times that force the use of parallel computation. Human error in multiple analyses is very likely and managing several analyses may become an additional challenge.

The authors' experience in providing CWM service for routine engineering lead us to believe that practical solutions will be found if a service provider becomes skilful in handling significantly large number of modelling analyses in a short time frame.

Weld fracture mechanics

Welded structures are likely to contain or form welding flaws in the weld region. These include porosity, cracks, metallic inclusions, etc. Although the ideal is a defect-free structure the nature of welding processes as well as service conditions under fatigue loading or creep at an elevated temperature necessitate inspection that detects defects in the structure before installation of in the course of service. Very often, the structure is a high-value asset and cannot easily go out offline for replacement or repair.

When repair is not possible, API 579/ASME FFS-1² (common in the US and Canada), or BS 7910³ (Europe and Canada) standards offer Fitness-For-Service (FFS) assessment at different levels. Using computer modelling of fracture behavior in flawed structure enabling reliable prediction of Remaining Useful Life (RUL) is becoming the most pursued technique under API 579 or BS 7910 FFS services. Based on these computational capabilities, the criticality of flaws or damages detected by visual and non-destructive methods can be determined, and the remaining life of the component/asset under particular service conditions predicted.

RUL calculations for defects are required on a case-by case basis in order to justify making fitness-for-service decisions. Crack growth is controlled by the SIF (Stress Intensity Factor) that depends on a combined global and local stress analysis of the joint with a flaw embedded. The shape, size, location, and orientation of the flaw needs to be considered from inspection, and the SIF recalculated for each increment of growth until a critical flaw size that leads to the final fracture.

Fatigue Weld Fracture

² ASME, API Recommended Practice 579, Fitness for Service, Washington D.C: ASME, 2016.

³ B. S. Institute, BS 7910 Guide to Method for Assessing the Acceptability of Flaw in Metallic Structures, London: BSI Standard Limited, 2013.



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API 579 and BS7910 ECA (Engineering Critical Assessment) under Fatigue FFS considers the life of sub-critical crack growth stage for the assessment. The assessment is based on the Paris-Erdogan law and the experimental measurement of fatigue crack growth rates (FCGR) in accordance with ASTM E647⁴.

BS7910 requires calculation of the parameter for plastic collapse L_r , and the fracture ratio K_r for each increment of crack growth. These parameters are used to determine the critical crack length by comparison to a material specific Failure Assessment Diagram (FAD).

Our Developed Methodology For ECA is Summarized Below:

- Using digitized radiographs a 3D map is created for each weld with embedded flaws. This map gives the location, size, shape and orientation of each flaw in the joint as well as the actual weld height and leg length.
- Based on this we prepare an initial model of each weld. We use numerical analysis (FEA) methods to determine the stress intensity factor (SIF), K , including at least two techniques of calculation e.g. J-Integral and CTOD (Crack Tip Opening Displacement). We report K if both techniques converge to a similar number.
- The crack growth direction is predicted by controlling SIF calculations over all nodes along the crack front in 3D coupled with sequential growth rates at each node, to evolve the planar shape of the crack. Figure 1 shows an example of the evolution of the crack front from an initial detected crack. This capability also enables us to determine if the joint will Leak-before-break.
- Using this information, a number of growth cycles is then calculated⁵. By converting the growth cycles to life, the critical times are determined for integrity management.

⁴ ASTM, Standard Test Method for Measurement of Fatigue Crack Growth Rates, ASTM International, 2013.

⁵ T. L. Anderson, Fracture Mechanics Fundamentals and Applications, Boca Raton FL: CRC Press, Taylor & Francis Group, 2005.



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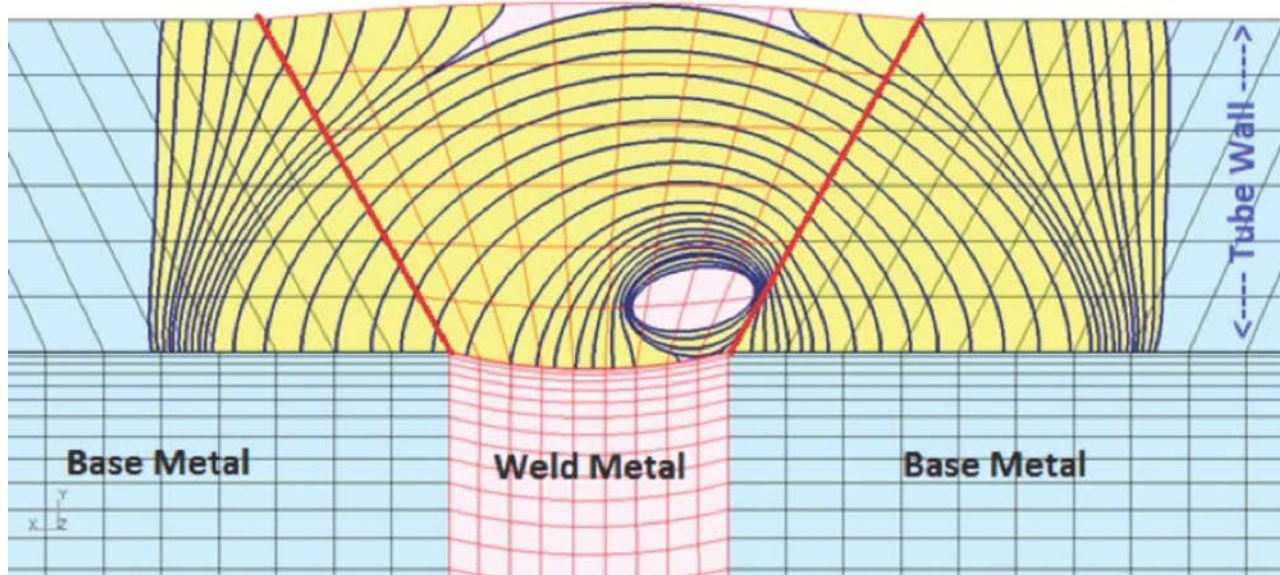


Figure 1 Crack front evolution from an initial crack detected in a tube butt weld

A Fatigue FFS Project

The name of client and other confidential information for the following discussion shall not be disclosed.

We were asked for ECA for a number of fillet welds and groove welds in the structure subject to fatigue loading. Our inspection crew reported that the welds contained linear type defects (lack of fusion, incomplete penetration, non-metallic inclusions). On a case-by-case assessment, we implemented the methodology explained earlier. Project time constraints were the key factor for the client to define the criticality of each joint and related plan of action including downtime.

Normally, there is more than a single flaw in any particular joint, and multiple joints containing a flaws. A service provider might be able to complete an FEA-based FFS ECA in a short timeline as a fast response. However, dealing with tens of ECAs can only be beneficial to a client if managed in parallel in order to adhere project timelines. Such a project cannot be possible manually and must be parameterized and automated.

FFS standards are mainly written for RUL of planar type flaws or conservatively assume the closest planar crack shape to the flaw for RUL assessment based on the long crack growth stage of fatigue. This approach ignores the nucleation life because this life are very short when dealing



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with a planar type flaw. However, the nucleation life can be long (in some cases beyond the design life) for volumetric flaws such as spherical type defects.

Nucleation life can be determined by an S/N curve that is experimentally measured following ASTM E468 for stress controlled fatigue test of metallic materials or ASTM E606 for strain-controlled fatigue testing. As oppose to planar type flaws that require a case-by-case assessment, volumetric flaws can be analyzed in accordance with a general safe/unsafe region in the weld metal. A safe region, for each weld, is determined by comparing the resultant stresses for a series of simulated defects and a threshold peak stress observed through simulation of a defect-free weld.

Creep Weld Fracture

As with fatigue, creep damage is a progressive and localized structural damage mechanism. Elevated temperature introduces new mechanisms of creep plastic flow or creep damage that are temperature, stress and microstructure dependent. A Creep Deformation Mechanisms Map (DMM) is a diagram that summarizes all mechanisms and associated active ranges for different materials. Most creep models (e.g. Larson-Miller or Omega model in API 579) are developed for the creep damage mechanism which is less sensitive to variation in microstructure than actual creep mechanism that is active in service condition, and therefore no microstructure term appears in the formulation⁶.

Actual service life failure in P91 structures, are most often observed in the Heat Affected Zone (HAZ) of weld where variation in microstructure is sharp and significant. Considering the typical operational temperature and stress for P91 materials, the dominant creep mechanisms and the creep rate is greatly dependent on the microstructure state. Therefore a model must include microstructure changes for a realistic prediction. In addition to the microstructure effect, welding residual stress (WRS) is also present in HAZ and therefore must be addressed. The models discussed herein define the Crack Critical Location(s) (CCL) where a creep crack forms and Paris-Erdogan law can be used to determine the RUL.

A Creep FFS Project

The project was creep life prediction of a P91 pipe under an operational temperature of 700 [K], subjected to non-uniform stress distribution including combined residual stress from welding and

⁶ J. Z. L. M. Asadi, "An Integrated Welding and Damage Model for Practical Prediction of Creep Life in Welded P91 Alloy," in ASME 2016 Pressure Vessels & Piping Division, Vancouver BC, 2016.



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10 [bar] internal pressure. The weld was made with two GTAW passes - root and cap weld passes with the joint preparation shown in Figure 2.

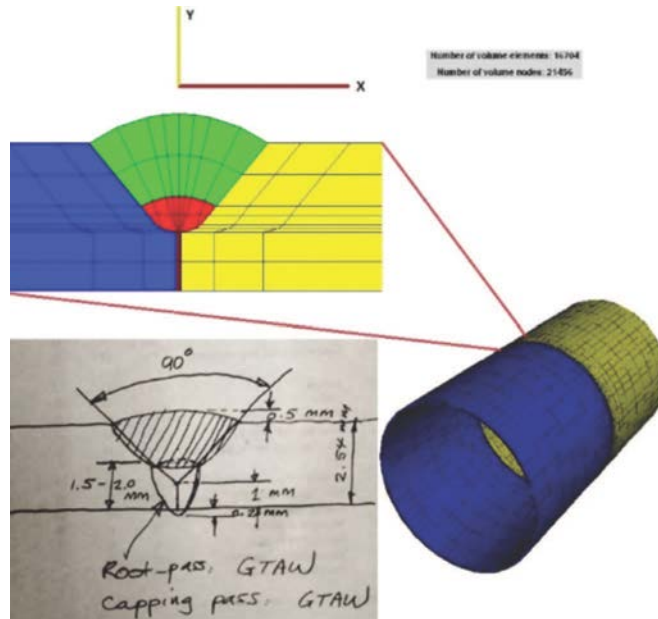


Figure 2 Mesh and weld cross section modelled for crack life prediction

The project started with welding modelling including a 3D model of the full welding procedure specification (WPS) provided. Figure 3 illustrates a snapshot of the transient temperature field when the weld cap is approximately 50% completed.

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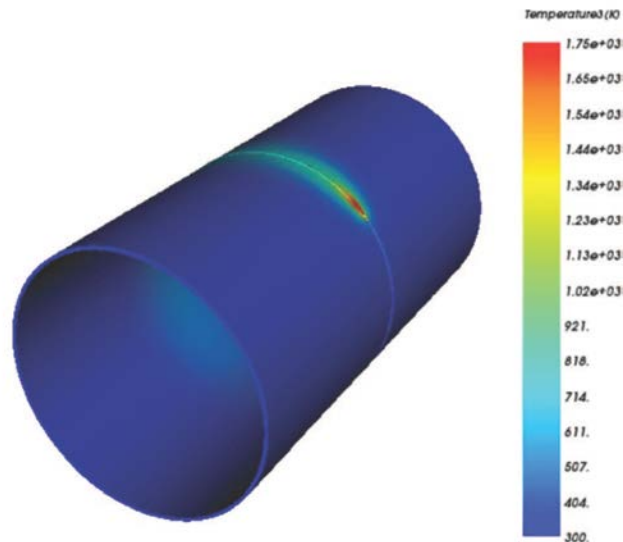


Figure 3 Transient temperature when the cap weld passes half weld path

The result of thermal modelling of welding process is the thermal profile history for every node of weld metal, HAZ, and base metal pipe. These profiles were fed into a microstructure solver to predict key creep microstructure parameters, namely grain size (GS), precipitation size (PS), and precipitation interspacing (PI) for every node based on a table of correlation between the peak temperature and observed microstructure. Figure 4 shows 3D map of average grain sizes after welding.



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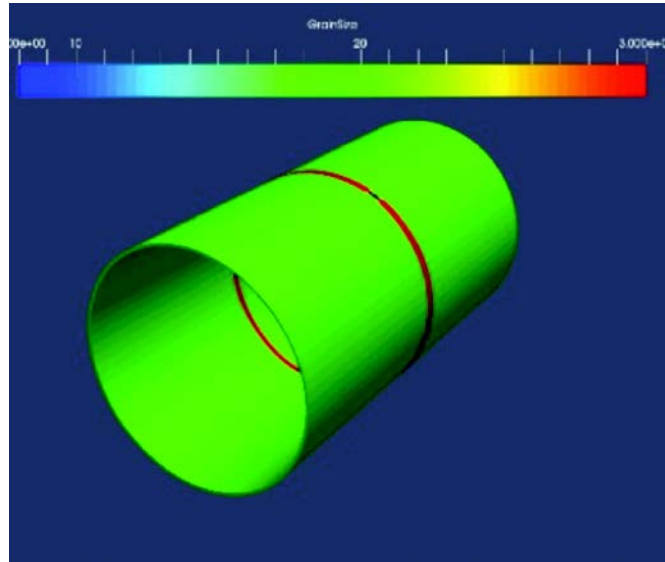


Figure 4 3D map of average grain size

For creep assessment we need to define both nodal operating temperature and stress. Nodal temperature was calculated by thermal FEA under the operating condition. To accommodate the effect of WRS, the welding residual stress was calculated using a FEA model, scaled and smoothed using an empirical relation developed for P91 to reflect the post weld heat treatment (PWHT) required by code for stress relief. This stress was initialized at the FEA nodes and the stress was re-solved when the internal operational pressure (10 [bar]) at operational temperature (700 [K]) was applied to the pipe. The new stress-strain state was used for creep life prediction. Figure 5 shows a 3D map of WRS in the weld metal, the HAZ and the pipe parent metal.

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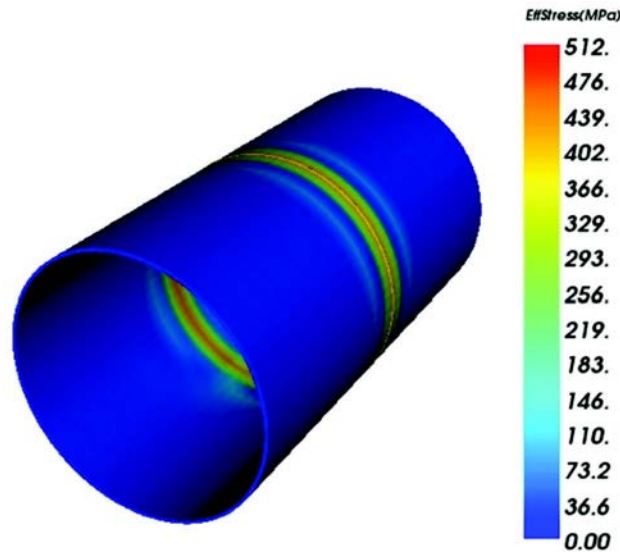


Figure 5 Welding residual stress

A validated DMM for P91 that covers the full range of stress and temperature and is a function of microstructure GS, PS, and PI was used to determine the nodal creep rate for every node based on the nodal state of microstructure and the stress and temperature exposure. These rates were then converted to life as shown in Figure 6. Other than the start end location of welding that shows an irregular red region, there are two rings of poor creep resistance on either side of the weld in the HAZ. This is conforms to the observations in the field.

If the assessment is based on a safe life approach that requires time to nucleation of a crack, this will define CCL(s) and inspection intervals. If the assessment is based on the damage tolerance, additional life can be calculated for the crack growth.

Conclusion

The use of simulation models is now routine in many areas of engineering; however, welding is among the few fields where engineering decisions remain generally traditional. Despite simulation packages that are now capable of supporting decisions based on quantitative analysis, there is little application in practice: Firstly, there is a shortage of skill in modelling and simulation, and secondly there is a need for automation to reduce the cost of analysis by making more effective use of the user's time, and for more efficient CPU time allocation. The authors hope that their experience encourages welding engineers to more frequently use simulation models for routine engineering.



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