

Fatigue Characterization of Welded Joints

Tech Brief 190801 F



Integrated Systems Research, Inc.
 August, 2019
steve.carmichael@isrtechnical.com

Abstract:

Weld fatigue characterization as formulated by AWS, AISC, TWI, and many other organizations takes an approach of classifying stress life curves based on joint categories without reference to specific alloys or mean stress effects. This Tech Brief discusses the warrants grounding this methodology but also reviews how design practices and post weld operations can substantially improve fatigue performance beyond these characterizations.

Both strain life and fracture mechanic methods are used to illustrate the mechanisms supporting the basis of the fatigue characterizations, simultaneously revealing the options at the disposal of a designer to improve performance.

Background:

Stress life curves for welded joints are typically presented as shown below in the AWS D1.1-90 chart in Figure 1 for dynamically loaded structures. The curves are characterized based on a joint category system. The allowable design stress is presented as a stress range rather than alternating stress with no mean stress effects considered. The curves represent a -2σ life cycle prediction. The lack of material alloy designation associated with the curves is the most obvious missing parameter typically considered to be part of a fatigue characterization.

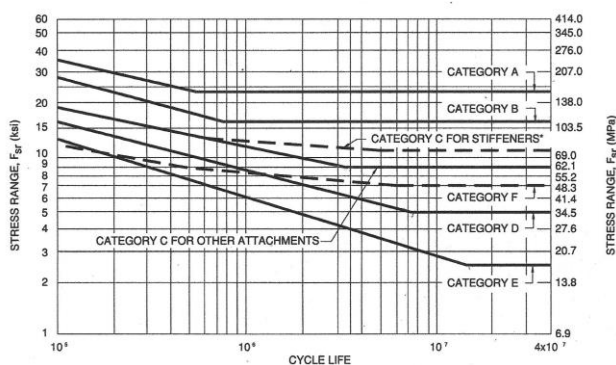


Figure 9.3—Design Stress Range Curves for Categories A to F—Nonredundant Structures (see 9.4)

Figure 1 – AWS Weld Joint Fatigue Characterization

The empirical warrant, however, for characterizing fatigue performance of as-welded joints independent of the parent metal strength is ubiquitous. Figure 2 is an example of this phenomenon. The test data is for a Type F classified weld, employing alloys which have yield strength varying from less than 50 to over 100 ksi. For life cycles greater than $1E5$, the lower strength tends to outperform the higher strength alloys in fatigue. Increased monotonic strength does not necessarily result in improved fatigue performance with joints placed in service as-welded.

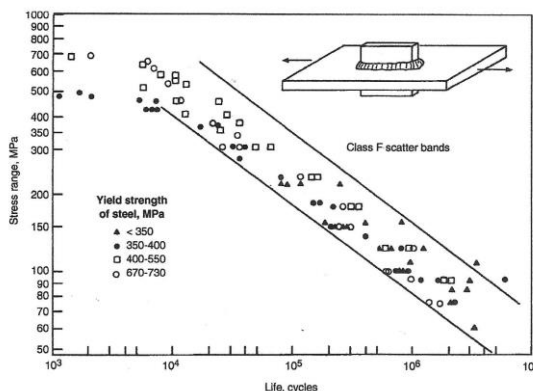


Figure 2¹

The mechanisms contributing to this behavior are multifaceted, but the primary factors are higher residual stresses with higher yield strength alloys and less ductility in the Heat Affected Zone (HAZ) grain structure resulting in higher effective stress concentrations from reduced blunting at geometric discontinuities.

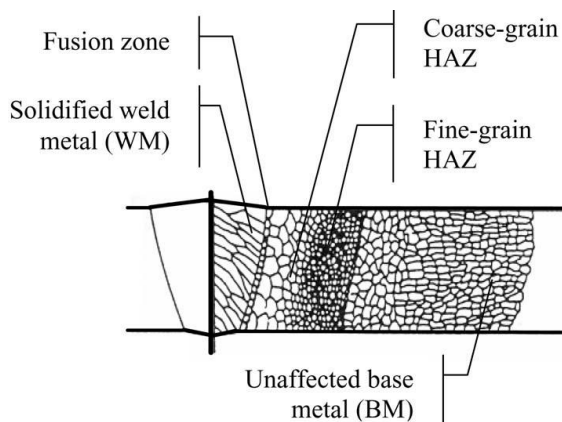


Figure 3 – Microstructure of Welded Joint

¹ ASM Handbook Vol 19 Fatigue and Fracture p. 440

Strain life methodologies are used in this tech brief to demonstrate the warrant for fatigue characterization of as-welded joints as provided by AWS, TWI, and AISC. In doing so, it provides the basis for employing strain life analyses to quantify the benefits of addressing the sources of uncertainty in weld joint fatigue estimates. The strain life methods bring both explanatory power to empirical observations and a means of quantifying the benefits of addressing the sources of uncertainty in fatigue performance by using post weld operations. This informational content cannot be found in AWS, TWI, or AISC fatigue design curves.

Sources of Uncertainty:

From a design standpoint, the greatest source of uncertainty, when using AWS, TWI, or AISC weld stress life curves, is the weld categories themselves. Very few welded joints fall neatly into a single category. Aligning the load transfer of an actual joint with examples used for categorizing the joint detail is more art than science. The uncertainty associated with the chosen fatigue characterization can result in either overdesigning joints or creating exposure to unacceptable risk.

In addition to gross load transfer characteristics, local geometric details also can have a significant influence on fatigue performance. Welding inherently creates non-controlled geometric features which typically are sites for crack initiation. Using a strain life approach to evaluate welded joints can reduce the uncertainty associated with these features as well as quantify the benefits of post weld operations.

Another major source of uncertainty is the microstructures created in the welding process. Not only is the alloy's microstructure changed but the process produces intrusions in the fusion zone that grow into macro cracks governed by the Paris equation. This can be viewed as a form of crack initiation evaluated by determining whether, for a given stress range, the threshold value is exceeded when the intrusion reaches the transition length of a micro to macrocrack. Not exceeding the threshold stress intensity at the transition length provides additional warrant for accepting the lower bound life cycle estimate obtained from a strain life analysis.

Microstructure changes in the HAZ also influence the ductility of alloy in regions where the highest stress concentrations occur. Lower ductility results in a decrease of blunting in local features creating higher effective stress concentrations (k_f). Variation in HAZ properties as well as blunting models are other sources of uncertainty in the expected fatigue life of welded joints.

Manufacturing Techniques to Address Uncertainty:

Post Heat Treatment

Addressing the changes in microstructure is the primary reason for weld repaired castings oftentimes undergoing normalization. Post heat treating above the transformation temperature enables the microstructure in the HAZ to become recrystallized forming properties similar to the parent material.

The most common form of post heat treatment, however, is stress relief which occurs below the transformation temperature. The intent is solely to reduce the residual tensile stresses in the HAZ.

The stresses produced by internal strains are self-equilibrating. When reducing the level of tensile stresses, compressive stresses in the joint are also being lowered. The desired goal of increasing the life cycles to crack initiation is facilitated by reducing the residual tensile mean stress, but it has been observed that cracks, once initiated, can propagate at a higher rate in stress relieved joints.² The lower compressive stresses, away from the initiation site, would be the most likely reason for this observed phenomenon.

Post Induced Residual Stresses

Post weld operations that are not related to heat treatment but attempt to create a more favorable mean stress condition at potential crack initiation sites are shot/needle and hammer peening. The intent of these techniques is to create compressive stresses at potential crack initiation sites. Since these processes result in self-equilibrating internal strains, tensile stresses in the joint are induced as well. Care in executing these procedures is required to ensure that

² Welding Research Supplement, 485-S, 1972, Fatigue Crack Propagation in A514 Base Plate and Welded Joints, Parry, Norberg, and Hertzberg

tensile stresses are not inadvertently created at prime initiation sites.

Local Weld Geometry

Addressing the local geometry of the weld toe is typically done through one of two ways. The first is disc grinding where a small undercut is ground to remove the near singularity created at the weld toe. This also removes intrusions created at the fusion to HAZ interface which is the primary intent of the technique.

Another technique associated with weld geometry is a re-melting process associated with TIG or plasma dressing the toe. This re-melt has the potential benefits of improving the toe profile and burning away or moving the intrusions away from the weld toe geometry.

A third approach, as with the first technique, is a machining operation which is intended to reduce the limiting stress concentration. This is done by grinding the profile of the throat as well as the toe of the weld. The weld toe is shielded by contouring the path through which the load is transferred reducing the effect of the geometric discontinuity. The strain life fatigue evaluation in the next section illustrates the potential benefit this type of operation can provide. Grinding operations, however, need to be undertaken with care since surface residual stresses can also result from the process.

Reducing Uncertainty with Strain Life Methodologies:

Employing strain life analytical methods³ to assess crack initiation in welds provides a means of quantifying the benefits of incorporating specific weld details in joints and/or post weld techniques to address the sources of uncertainty in fatigue performance. The methodology uses strain life parameters, Neuber's flow or SED rules, and Morrow or SWT mean stress models to estimate the true stress-strain states at limiting fatigue sites and correlate the alternating strain with an expected number of life cycles to initiation.

³ [Estimating Notch Strains with Net Section Plasticity](#) – This reference that covers several methods for true stress-strain estimates employing strain life data

With this approach, the uncertainty associated with the category of weld joint is eliminated. The analyses can be parameterized to efficiently enable other sources of uncertainty to be quantified and therefore meaningful value assigned to the use of post weld operations in enhancing fatigue life.

Example of Cruciform Weld Joint:

Maximum Effective Stress Concentrations K_f

Significant work was done in the 1970s and early 80s in the Fracture Control Program (FCP) at the University of Illinois on the fatigue behavior of welded joints. A consortium of companies provided funding for the program and one of the lead researchers, F.V. Lawrence, employed a strain life approach to correlating observed fatigue behavior to analytical predictions.

The cruciform weld joint in Figure 4 illustrates the use of this approach in evaluating the fatigue characterization of a welded joint.

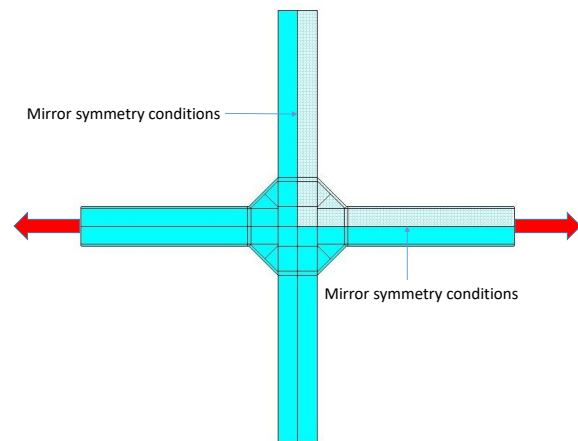


Figure 4 – Cruciform Weld Joint Model

In correlating empirical data with analytical predictions, Lawrence developed a concept known as maximum k_f . The concept employs Peterson's blunting model to estimate a maximum effective stress concentration that can be developed as a function of material ductility and load path geometry⁴. Employing this tool, joints with non-controlled

⁴ [Estimating Fatigue Blunting Employing Stress Intensity Fields](#). This tech brief reviews Peterson's blunting model and limitations.

geometric features can be evaluated based on the assumption that the maximum k_f is present.

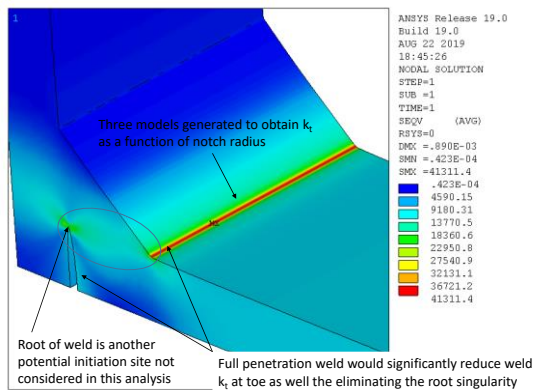


Figure 5 – FE Result Used in Analysis

When the k_t function of a joint feature is substituted into the notch sensitivity equation in Peterson’s blunting model the maximum k_f can be estimated. A closed form solution can be obtained by taking the derivative of the equation and finding the notch radius at which the derivative is zero. That value is then back substituted into Peterson model to find k_f . Graphically, this is shown in Figure 6.

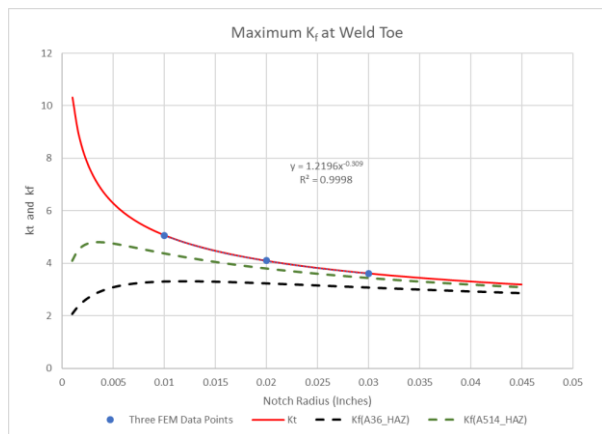


Figure 6 – Maximum k_f at Toe of Fillet Weld

For the weld geometry shown in Figure 5, the maximum k_f is 4.8 for A514 and 3.31 for A36. This is one of the reasons for fatigue performance in as-welded joints being relatively independent of alloy selection. A514 has a yield strength of over 2.5 times A36, but its lower ductility in the HAZ tends to create higher effective maximum stress concentrations offsetting the potential benefit of the superior mechanical strength properties.

Figures 7 and 8 illustrate the influence local geometry can have on the maximum k_f in a joint. Figure 7 is the same cruciform joint but with a slight concavity in the throat of the weld. The maximum k_f for A36 is reduced by 14% and by 22% for A514.

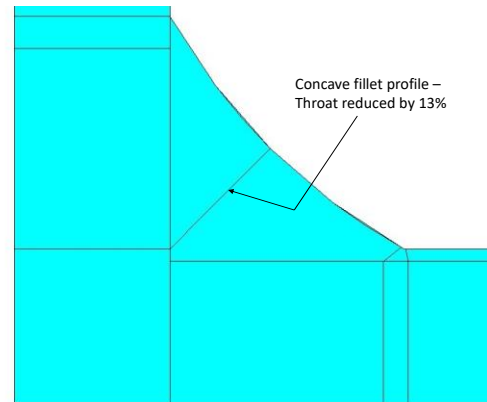


Figure 7 – Local Change to Fillet Throat Geometry

The change in throat net section is 13% which reduces the concentration of the re-entry load around the weld toe as it is transferred into the throat net section.

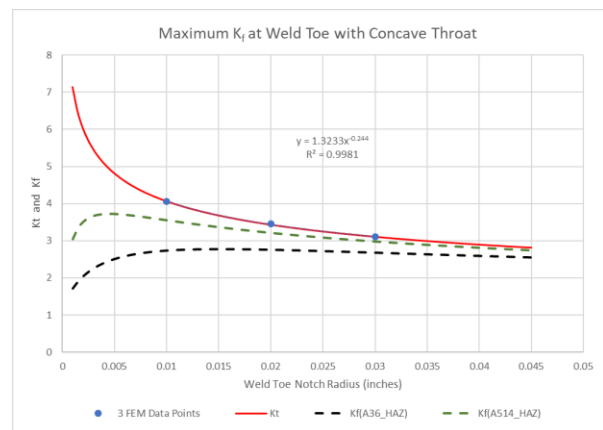


Figure 8 – Maximum k_f at Toe of Fillet Weld

The load path itself and not just the size of the notch radius contributes to the effective stress concentration in a joint. Employing a strain life methodology in evaluating welded joints enables a designer to quantify the performance benefits of post heat treatments, machining operations or change in alloy selection so that actual total costs are minimized.

Geometry, material fatigue parameters, and residual stress influences are all incorporated into a strain life

approach. This enables a designer to coherently address the three variables which control the performance of all structures; geometry, materials, and loads.

Fatigue Characterizations of Cruciform Welds

Fatigue characterization for the cruciform welded joint are shown in Figures 9 and 10 for A36 and A514. A strain life methodology using a Morrow mean stress model and HAZ strain life fatigue parameters obtained from the Fracture Control Program at the University of Illinois were employed. The residual stress level is assumed to be 60% of the parent material yield strength. These characterizations are approximately -2σ design curves. The red curve is the baseline joint based on the parent material with a yield less than 50 ksi. The as-welded curves are well aligned with the AWS category C design curve.

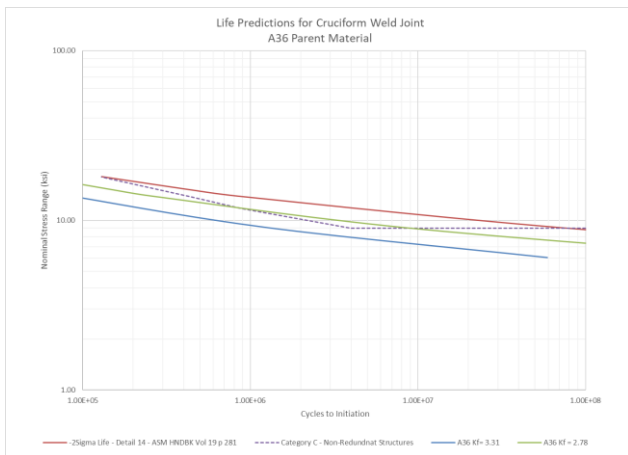


Figure 9 – Characterizations for A36

The green curve is the design limits for the joint with the concave throat profile. The straight weld profile has the maximum $k_f = 3.31$ and the concave profile a $k_f = 2.78$. The difference in the -2σ life predictions at a stress range of 10 ksi is approximately an order of magnitude for the two welds. Both the potential performance benefit and risk of relying on this particular post weld operation are captured in this minor weld profile modification.

A similar scatter is seen in Figure 10 for the joint fabricated with A514. Additionally, the A514 provides an upper and lower bound of the welded connection fabricated using an alloy having a yield strength less than half the value of A514.

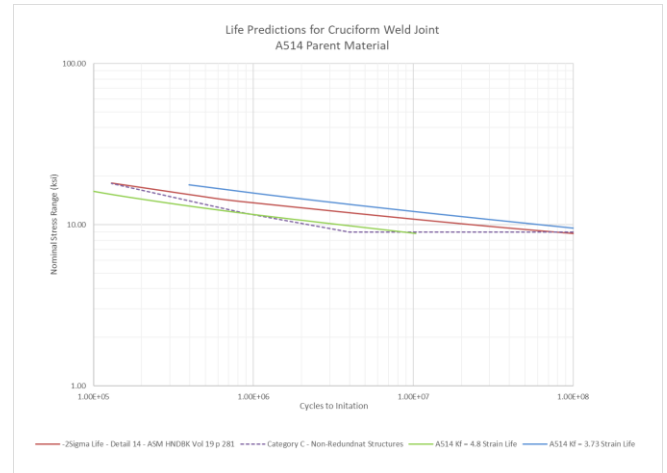


Figure 10 – Characterizations for A514

Figure 11 is a fatigue characterization for A514 employing LEFM. For a given life cycle prediction, threshold data obtained from work done by Maddox was used to evaluate the stress range which would not exceed the threshold stress intensity assuming an intrusion being present at the transition length from a micro to macro crack⁵. These characterizations represent a probability of survival of approximately 98%.

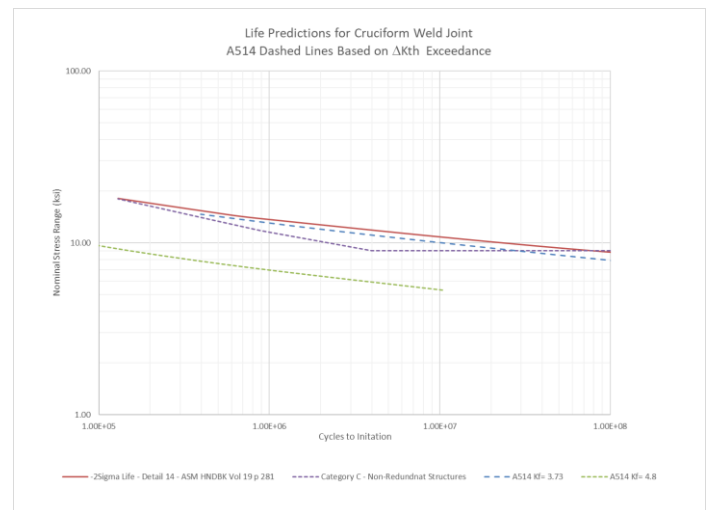


Figure 11 – Characterizations Using LEFM

⁵ [Damage Tolerance Assessment Using Stress Intensity Threshold Values](#), equation 7.0, page 4

Conclusions:

The strain life welded joint fatigue characterizations are in good agreement with standard AWS, TWI and AISC as-welded design curves. Due to the loss of ductility and higher residual stresses in the HAZ there is typically no significant advantage to using higher strength alloys in as-welded joints. Higher strength alloys, however, can provide improved performance when post weld operations are employed.

Strain life methods bring significant value to characterizing welded joints by eliminating the uncertainty associated with categorizing a specific joint design into a classification system and providing a means of quantifying the post weld operations benefits. The strain life analysis method provides high informational content in guiding the design activity, especially when the use of post weld operations are under consideration to enhance the fatigue life of welded joints.