

Evaluating the Flaw Tolerance and Ductile Tearing Resistance of Austenitic Stainless Steel Welds

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ABSTRACT

In general, austenitic stainless steels behave in a more ductile than brittle manner and do not typically experience a ductile-to-brittle transition like typical ferritic steels. Furthermore, the fracture toughness of austenitic stainless steels is ordinarily high, even at low temperatures, provided the material has not experienced any notable in-service degradation in fracture toughness. Often, it is more likely for an existing crack-like flaw in an austenitic stainless steel pressure vessel or piping component to experience ductile tearing than to initiate a brittle fracture. For this reason, the Level 3 ductile tearing analysis methodologies described in Part 9 of API 579-1/ASME FFS-1, Fitness-For-Service (API 579) [1] are summarized in this paper and compared to conventional elastic-plastic fracture mechanics (based in the use of the failure assessment diagram, per API 579). Additionally, in this paper, a case study is summarized where identified crack-like flaws in an austenitic stainless steel reactor are analyzed for ductile tearing to gain perspective on the propensity of the existing cracks to cause a catastrophic failure of the pressure boundary. A conventional brittle fracture assessment is performed for comparison purposes using a lower bound fracture toughness value for stainless steel weldments, based on published data. These calculations account for primary stress (from internal pressure) and weld residual stresses. Understanding the fracture and ductile tearing resistance of austenitic stainless steel welds in pressure equipment is an important aspect of managing the risk associated with operating components that may be prone to crack initiation and propagation due to operational and environmental conditions. Relevant damage mechanisms include reheat (stress relaxation) cracking, high-temperature creep, thermal or mechanical fatigue, and stress corrosion cracking. Leveraging fracture mechanics-based fitness-for-service approaches, as discussed in this paper, for qualifying

crack-like flaws can extend equipment life and minimize the need to perform costly repairs or component replacement.

Key words: Ductile Tearing, Fracture Mechanics, Austenitic Stainless Steel, Crack-Like Flaws, Brittle Fracture, Fitness-For-Service, Weld Residual Stress, Risk Management

INTRODUCTION

As discussed in Reference [2], austenitic stainless steel alloys are used extensively in heat-resistant structural components in the oil refining, power-generation, and chemical industries as a result of their metallurgical stability, excellent corrosion resistance, and good creep and ductility properties at elevated temperatures. Additionally, 300-series stainless steels are the most widely used structural alloys for cryogenic applications, because they exhibit high strength, ductility, and fracture toughness properties. In general, austenitic stainless steels behave in a more ductile than brittle manner and do not typically experience a ductile-to-brittle transition like ferritic steels; however, a toughness transition may occur in austenitic stainless steels with high ferrite content. Furthermore, for austenitic stainless steels, the fracture toughness is ordinarily high, even at low temperatures, provided the material has not experienced any significant degradation in fracture toughness. For pressure equipment constructed of austenitic stainless steel, it is possible for an existing crack-like flaw to experience ductile tearing rather than to initiate a brittle fracture. Part 9 of API 579-1/ASME FFS-1, Fitness-For-Service (API 579) [1] contains a step-by-step procedure for evaluating the propensity for crack-like flaws to cause a catastrophic failure of the pressure boundary. This includes conventional brittle fracture assessments, using the Failure Assessment Diagram or FAD, and ductile tearing assessments. For austenitic stainless steels, damage mechanisms that often cause crack-like flaws include reheat (stress relaxation) cracking, high-temperature creep, thermal or mechanical fatigue, and environmental stress corrosion cracking (most often at or near welds).

In this paper, commentary on the API 579 [1] procedures for evaluating brittle fracture and ductile tearing, specifically at welds, is provided. Additionally, a case study is summarized that relates to crack-like flaws identified near bottom head welds on an austenitic stainless steel reactor. Ductile tearing calculations are carried out to quantify the risk associated with continued operation. Conventional brittle fracture calculations are also performed for comparison purposes using a lower bound toughness value for stainless steel weldments, per API 579 [1]. These fracture calculations account for conservative primary stress (from maximum internal pressure) and weld residual stresses. The intent of this case study is to offer some perspective on the propensity for a ductile tearing-type failure mode and to establish a recommended depth threshold (critical size) for a given crack-like flaw. The results of this assessment can be leveraged to determine the most practical and appropriate path forward for the identified flaws (run vs. repair, etc.) and to quantify the risk associated with the cracking. In general, regardless of assessment outcome, periodic inspection/monitoring is recommended, if feasible, to ensure that any known crack-like flaws are not propagating in the through-wall or length directions.

LITERATURE REVIEW

Many publications address the fracture properties and ductile tearing resistance of austenitic stainless steel welds. A comprehensive paper by Mills [2] summarizes extensive fracture toughness testing of stainless steel alloys. This paper also summarizes the fracture toughness behavior of wrought base metals and welds. Minimum expected toughness values, based on statistical analyses of literature data, are provided for use in fracture mechanics-based evaluations. This paper [2] also offers a very detailed literature review, with 184 references discussed. Figure 1, taken from this paper, shows comparisons of J_c fracture toughness for different 300 series stainless steel welds, including gas-tungsten arc (GTA), gas-metal arc (GMA), shielded-metal arc (SMA), submerged arc (SA), and flux-cored arc (FCA) welds. The typical base metal toughness value for 300 series materials is also shown for information. The

values shown in this figure may not be representative of all possible welded material, especially for processes that use flux such as SMA, SA, and FCA. In these cases, fracture toughness values may vary considerably depending on the actual flux used.

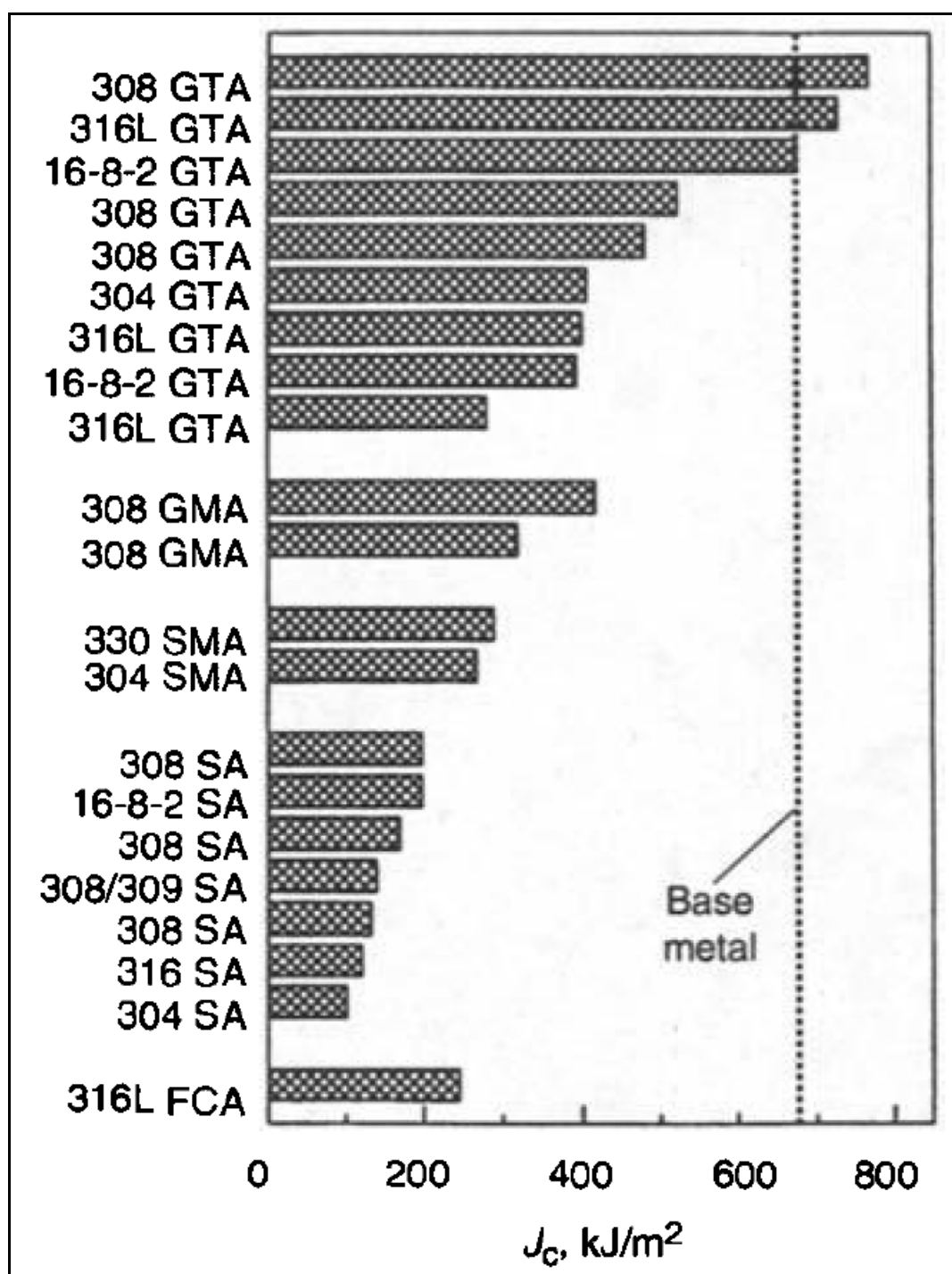


Figure 1: Fracture Toughness Comparison for 300 Series Stainless Steel Welds [2].

A very comprehensive reference that discusses ductile tearing (and provides ductile tearing properties for different steels) is the Electric Power Research Institute (EPRI) Ductile Fracture Handbook [3]. Additionally, as discussed in Reference [4], ductile fracture analysis consists of two components: crack driving force (J) and the material's resistance to crack extension. The driving force is calculated based on applied loading, geometry, and stress-strain properties of the material, and the crack growth

resistance is generally established based on laboratory testing (often compact tension specimens). The crack growth resistance is characterized by J-Resistance or J_R -Curves for a given material.

Many other technical papers address the topic of evaluating ductile tearing resistance in austenitic stainless steels. Daly et al. [5] performed an advanced assessment on the ductile tearing resistance of nuclear reactor pressure vessel steels using x-ray techniques. Another study by Jayadevan et al. [6] investigated the ductile tearing resistance of surface-cracked pipelines using a simplified approach. Reference [7] utilizes damage plasticity theory to evaluate ductile fracture initiation, and Reference [8] summarizes a ductile tearing simulation approach for pipes with circumferential cracks, where test results are directly compared to simulation results. Nam et al. [9] evaluated ductile tearing resistance of circumferentially cracked pipes under dynamic loading conditions. Dodds et al. [10] published test results to investigate the effects of prior ductile tearing on fracture toughness. Additionally, Ruggieri and Dodds provide a computational framework for quantifying the influence of constraint loss and ductile tearing on the cleavage fracture process in Reference [11]. Lastly, a detailed comparison of the mechanisms of brittle versus ductile fracture is given in Reference [12].

FAILURE ASSESSMENT DIAGRAM AND FRACTURE TOUGHNESS

As shown in Figure 2, the Failure Assessment Diagram (FAD) is used for the evaluation of crack-like flaws in components (consistent with API 579 [1]). The FAD approach was adopted in API 579 [1] because it provides a convenient, technically based method to determine the acceptability of a component with a crack-like flaw. In accordance with this approach, the driving force for failure is measured by two distinct criteria: unstable fracture and limit load. Linear elastic fracture usually controls failure in cracked components fabricated from a brittle material and plastic collapse at a limit load typically controls failure if the component is fabricated from a material with high toughness (high ductility). Elastic-plastic fracture occurs between these two extremes. In the analysis of crack-like flaws, the results from a stress analysis, stress intensity factor, limit load solutions, material strength, and fracture toughness are combined to calculate a toughness ratio (K_r) and a load ratio (L_r) for primary stress. These two quantities represent the coordinates of a point that is plotted on a two-dimensional FAD to determine acceptability. If the assessment point is on or below the FAD curve, the component is suitable for continued operation. Additional information on the FAD-based fracture mechanics approach is covered in References [13-15]. It is important to note that an iterative approach (varying pressure and temperature) can be employed to generate a minimum pressurization temperature (MPT) envelope for a given reference flaw size using the FAD. This essentially equates to a safe pressure - temperature curve for a given crack like flaw at a specific location in a piece of pressure equipment. For additional information on establishing MPT recommendations for pressure equipment, refer to References [16-17].

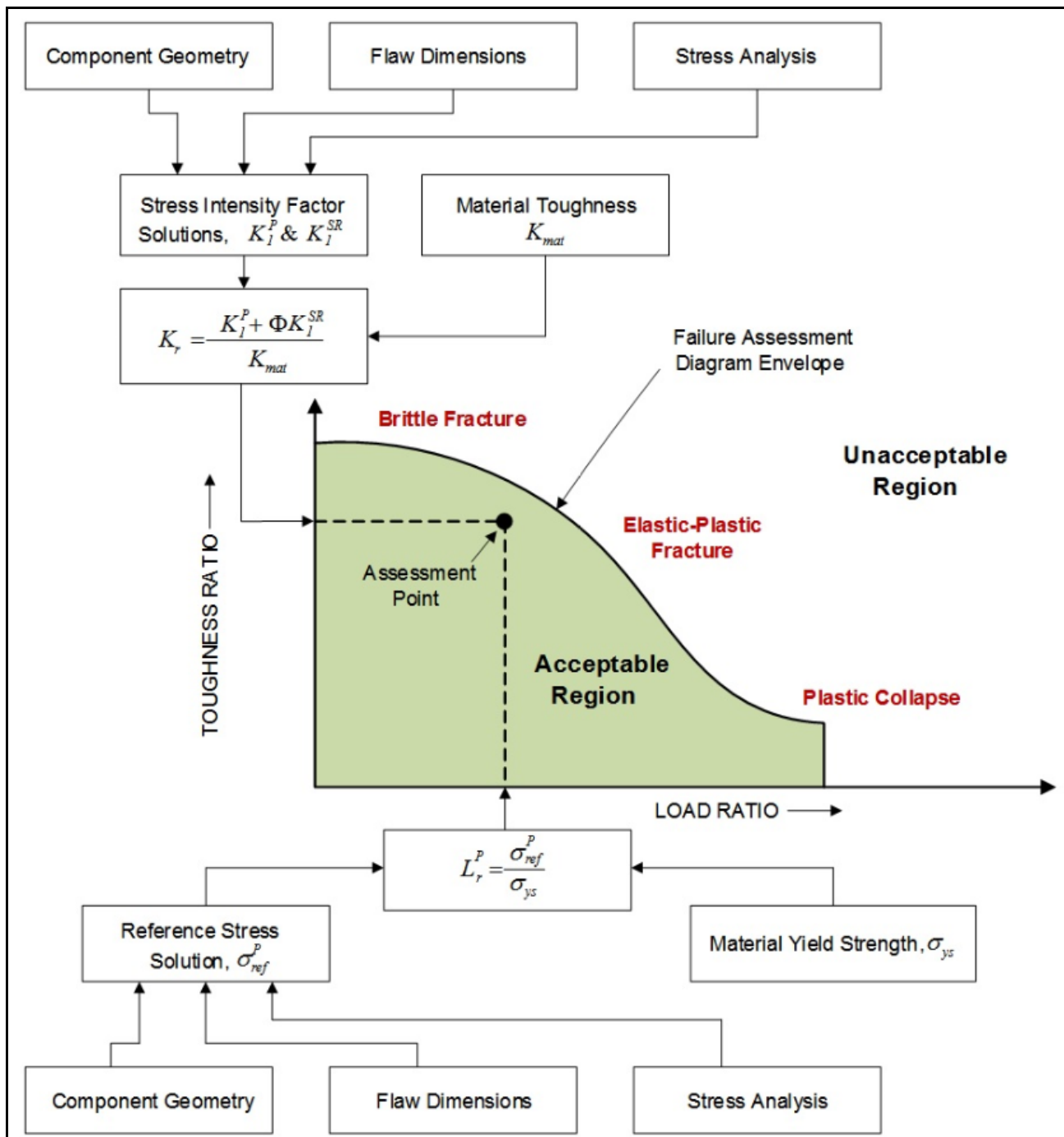


Figure 2: Failure Assessment Diagram Consistent with API 579 [1].

In this paper, conventional brittle fracture calculations are carried out assuming a lower bound toughness estimates consistent with the upcoming edition of API 579 and based on the paper by Mills [2] discussed above. Figure 3 shows the calculated lower bound fracture toughness, assuming submerged arc welding. The calculation uses the lower bound J_C value and is a function of the elastic modulus (E_{YT}) and Poisson's ratio (ν). Based on this approach, a lower bound weld fracture toughness of 109.3 ksi $\sqrt{\text{inch}}$ (120.1 MPa $\sqrt{\text{m}}$) is calculated. Note that the current edition of API 579 [1] indicates a lower bound toughness of 120 ksi $\sqrt{\text{inch}}$ (131.9 MPa $\sqrt{\text{m}}$) should be used for austenitic stainless steel welds (see Annex 9F) in the absence of other data.