INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

FRACTURE TOUGHNESS ANALYSIS OF ASTM A36 STEEL WELDED JOINTS: THE CRITICAL ROLE OF STRESS CONCENTRATORS

ANÁLISE DA TENACIDADE À FRATURA DE JUNTAS SOLDADAS DE AÇO ASTM A36: O PAPEL CRUCIAL DOS CONCENTRADORES DE TENSÃO

ANÁLISIS DE TENACIDAD A LA FRACTURA DE UNIONES SOLDADAS DE ACERO ASTM A36: EL PAPEL FUNDAMENTAL DE LOS CONCENTRADORES DE TENSIÓN

https://doi.org/10.56238/isevmjv5n2-009

Receipt of originals: 03/10/2026 **Acceptance for publication:** 03/10/2026

Erwin E. Alcala Mendoza[1], Cláudio Márcio de Freitas da Silva[2], Manuel E. Esteves Pairazaman[3], Claudia Vanessa Vargas Vilchez[4], Gerson Dennis Parejas Sinchitullo[5], Segundo Arístides Távara Aponte[6]

ABSTRACT
The traditional criterion for designing structural elements relies on the material's elastic limit, a practice that proved inadequate with the advent of welded structures susceptible to cracks. All materials contain imperfections like dislocations, pores, or inclusions, but cracks are the most critical as they act as stress concentrators, leading to catastrophic failure at loads below the design limit. This deficiency prompted the development of Fracture Mechanics, which introduces crack size as a third critical variable alongside load and material properties. Instead of mechanical strength, this field uses fracture toughness to quantify the critical combination of stress, crack size, and a material's resistance to crack propagation. A key design criterion is to calculate the critical crack size for a given load and, by applying a safety factor, determine the maximum allowable crack size for safe operation. This study investigates the influence of stress concentrators on the fracture toughness of ASTM A36 steel joints welded via the SMAW process, hypothesizing that the heat-affected zone (HAZ) is the most critical area. The primary objective is to identify the most fracture-critical zone within the weldment by experimentally determining the J-integral in the elasto-plastic regime. The findings are crucial for enhancing the design, quality assessment, and structural integrity of welded joints.

[1] Master of Science in Mechanical Engineering Design. National University Toribio Rodríguez de Mendoza de Amazonas. E-mail: erwinalcala@gmail.com Orcid: 0000-0001-9693-1456
[2] Dr. in Electronic Engineering and Computing. Volta Redonda University Center (UNIFOA). E-mail: claudio.marcio.de.freitas.da.silva@gmail.com Orcid: 0000-0001-9631-014X Lattes: https://lattes.cnpq.br/9126863705361216
[3] Dr. in Physics. National University Toribio Rodríguez de Mendoza de Amazonas. E-mail: manuel.esteves@untrm.edu.pe Orcid: 0000-0001-9456-53
[4] Master`s degree in University Teaching and Research. National University Toribio Rodríguez de Mendoza de Amazonas. E-mail: docente509@untrm.edu.pe Orcid: 0009-0006-6413-78
[5] Master`s degree in Civil Engineering. Continental University. E-mail: gparejas@continental.edu.pe Orcid: 0000-0002-4733-0950.
[6] Dr. in Material Science. National University of Trujillo. E-mail: stavara@unt.edu.pe Orcid: 0000-0003-0415-6224.

Keywords: Fracture Mechanics. Crack Size. Fracture Toughness. Welded Joints. J-integral.

RESUMO

O critério tradicional para o projeto de elementos estruturais baseia-se no limite elástico do material, uma prática que se mostrou inadequada com a advento das estruturas soldadas suscetíveis a trincas. Todos os materiais contêm imperfeições como discordâncias, poros ou inclusões, mas as trincas são as mais críticas, pois atuam como concentradores de tensões, levando a falhas catastróficas sob cargas inferiores ao limite de projeto. Essa deficiência motivou o desenvolvimento da Mecânica da Fratura, que introduz o tamanho da trinca como uma terceira variável crítica, ao lado da carga e das propriedades do material. Em vez da resistência mecânica, essa área utiliza a tenacidade à fratura para quantificar a combinação crítica de tensão, tamanho da trinca e resistência do material à propagação de trincas. Um critério chave de projeto é calcular o tamanho crítico da trinca para uma dada carga e, aplicando um fator de segurança, determinar o tamanho máximo admissível de trinca para operação segura. Este estudo investiga a influência de concentradores de tensão na tenacidade à fratura de juntas de aço ASTM A36 soldadas pelo processo SMAW, hipotetizando que a zona afetada pelo calor (ZAC) é a área mais crítica. O objetivo principal é identificar a zona mais crítica à fratura no cordão de solda por meio da determinação experimental do integral J no regime elasto-plástico. Os resultados são cruciais para aprimorar o projeto, a avaliação de qualidade e a integridade estrutural de juntas soldadas.

Palavras-chave: Mecânica da Fratura. Tamanho da Trinca. Tenacidade à Fratura. Juntas Soldadas. Integral J.

RESUMEN

El criterio tradicional para el diseño de elementos estructurales se basa en el límite elástico del material, una práctica que resultó inadecuada con la aparición de estructuras soldadas susceptibles a grietas. Todos los materiales contienen imperfecciones como dislocaciones, poros o inclusiones, pero las grietas son las más críticas ya que actúan como concentradores de tensiones, provocando fallos catastróficos a cargas inferiores al límite de diseño. Esta deficiencia impulsó el desarrollo de la Mecánica de la Fractura, que introduce el tamaño de la grieta como una tercera variable crítica junto con la carga y las propiedades del material. En lugar de la resistencia mecánica, este campo utiliza la tenacidad a la fractura para cuantificar la combinación crítica de tensión, tamaño de grieta y resistencia del material a la propagación de grietas. Un criterio clave de diseño es calcular el tamaño crítico de la grieta para una carga dada y, aplicando un factor de seguridad, determinar el tamaño máximo admisible de grieta para una operación segura. Este estudio investiga la influencia de los concentradores de tensión en la tenacidad a la fractura de uniones de acero ASTM A36 soldadas mediante el proceso SMAW, hipotetizando que la zona afectada por el calor (ZAC) es el área más crítica. El objetivo principal es identificar la zona más crítica a la fractura dentro del cordón de soldadura mediante la determinación experimental del integral J en el régimen elasto-plástico. Los hallazgos son cruciales para mejorar el diseño, la evaluación de calidad y la integridad estructural de las uniones soldadas.

Palabras clave: Mecánica de la Fractura. Tamaño de Grieta. Tenacidad a la Fractura. Uniones Soldadas. Integral J.

INTERNATIONAL SEVEN JOURNAL OF MULTIDISCIPLINARY
ISSN: 2764-9547

1 INTRODUCTION

The conventional design of structural components, based on comparing the applied stress with the material's yield strength, has proven insufficient, particularly for welded structures [13, 17]. The introduction of welding revealed the vulnerability of structures to pre-existing or process-induced defects such as cracks, pores, and inclusions [6]. These defects, especially cracks, act as significant stress concentrators, which can lead to catastrophic failure at stress levels well below the material's nominal yield strength [3, 7].

This limitation of traditional design led to the development of Fracture Mechanics, a field that provides a more realistic framework for assessing structural integrity. It incorporates three key parameters: the applied load (σ), the crack size (a), and the material's fracture toughness [8, 14, 22]. While Linear Elastic Fracture Mechanics (LEFM) is suitable for brittle materials, Elasto-Plastic Fracture Mechanics (EPFM) is necessary for ductile materials like structural steels, where significant plastic deformation precedes fracture [2, 13].

1.1 LITERATURE REVIEW

The Shielded Metal Arc Welding (SMAW) process is widely used in construction and manufacturing due to its versatility and low cost. However, the thermal cycle inherent to welding creates a heterogeneous joint with distinct microstructural zones: the fusion zone (FZ), the heat-affected zone (HAZ), and the unaffected base metal (BM). Each zone possesses different mechanical properties, with the HAZ often being the region most susceptible to fracture initiation due to phenomena like grain coarsening and the formation of brittle phases [1, 11, 18].

Previous research has extensively documented the microstructural changes in welded joints of ASTM A36 steel and other similar carbon steels. Studies have correlated welding parameters, such as heat input, with the resulting microstructure and mechanical properties like hardness and tensile strength [19]. However, while the general principles of fracture mechanics are well-established, there has been a lack of detailed experimental studies applying EPFM parameters, specifically the J-integral, to systematically compare the fracture toughness of all three distinct zones (BM, FZ, and HAZ) in an ASTM A36 steel joint welded with the common E7018 electrode. Most analyses tend to focus on a single region or use less precise toughness evaluation methods.

INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

This study aims to fill this gap by conducting a rigorous comparative analysis of the fracture toughness across the entire weldment using the J-R curve methodology as prescribed by the ASTM E1820 standard. By precisely locating the crack tip in the base metal, fusion zone, and heat-affected zone, this research seeks to unequivocally identify the most critical region for fracture initiation and correlate its toughness directly with its specific microstructure. This provides crucial data for improving the reliability and structural integrity assessments of these ubiquitous welded components.

1.2 ARTICLE STRUCTURE

The remainder of this paper is structured as follows: Section 2 presents the theoretical fundamentals of Fracture Mechanics. Section 3 details the experimental methodology. Section 4 presents and discusses the obtained results. Section 5 summarizes the main conclusions, and Section 6 provides recommendations for future work.

2 THEORETICAL FUNDAMENTATION: FRACTURE MECHANICS

Fracture Mechanics analyzes the behavior of materials containing cracks [22]. Its main goal is to prevent structural failures by understanding the conditions under which a crack propagates.

2.1 LINEAR ELASTIC FRACTURE MECHANICS (LEFM)

LEFM applies when plastic deformation at the crack tip is negligible [2]. The core parameter in LEFM is the stress intensity factor (K), which describes the stress field at a crack tip [17]. Fracture is predicted when the applied stress intensity factor, K_I, reaches a critical material property, the fracture toughness, K_{Ic} [21]. A key limitation of LEFM is the requirement of small-scale yielding, which is often not met in ductile structural steels [2, 7].

2.2 ELASTO-PLASTIC FRACTURE MECHANICS (EPFM)

When extensive plastic deformation occurs at the crack tip, EPFM must be applied [2, 13]. EPFM utilizes parameters like the J-Integral and Crack Tip Opening Displacement (CTOD) to characterize fracture toughness in ductile materials. These parameters remain the state-of-the-art for such assessments, as evidenced by their widespread use in recent

INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

investigations on structural steel welds [2, 10, 15].

2.2.1 J-Integral

Introduced by Rice, the J-Integral is a path-independent line integral that measures the stress-strain field around the crack tip and represents the energy release rate in a nonlinear elastic material [12, 13]. For linear-elastic materials, J is related to K by [5]:

$$J_{el} = \frac{K^2(1-\nu^2)}{E} \tag{1}$$

Where:

E is Young's modulus and v is Poisson's ratio. The total J is the sum of its elastic and plastic components [5]:

$$J = J_{el} + J_{pl} \tag{2}$$

Fracture initiation in the ductile regime is considered to occur when the J-integral reaches a critical value, J_{Ic} [3]. This is typically determined from a J-R curve, which plots J versus stable crack extension (Δa) [2].

2.2.2 Crack Tip Opening Displacement (Ctod)

Proposed by Wells, CTOD (δ) is another key EPFM parameter that measures the displacement at the crack tip due to plastic deformation [6, 12]. It recognizes that in ductile materials, the crack tip blunts before propagation [12]. Fracture is governed not by a critical stress, but by reaching a critical plastic strain at the crack tip, which is characterized by a critical CTOD value, δc [6, 13]. The CTOD can be calculated from the J-integral using the following relationship defined in standards like ASTM E1820:

$$\delta = \frac{K^2(1-\nu^2)}{mE\sigma_Y} + \frac{J_{pl}}{m\sigma_Y} \tag{3}$$

where σ_Y is the material's yield strength and m is a constraint factor, which depends on the stress state and geometry (typically between 1 and 2).

INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

3 METHODOLOGIES

This study followed experimental procedures based on established standards to characterize the welded joint and evaluate its fracture toughness [1].

3.1 MATERIALS AND WELDING

The base material used was a 25.4 mm thick plate of ASTM A36 structural steel [1]. The joint was welded using the Shielded Metal Arc Welding (SMAW) process with AWS E-7018 electrodes. The chemical composition and mechanical properties of the materials are detailed in Tables 1 and 2. The welding parameters are listed in Table 3.

3.2 MECHANICAL AND MICROSTRUCTURAL CHARACTERIZATION

Standard procedures were followed for material characterization. This included metallographic analysis using a 2% Nital etchant, Rockwell B hardness measurements across the weldment, and tensile tests according to the ASTM E8M standard [1, 4].

Table 1

Chemical composition and mechanical properties of the ASTM A36 base metal [1]

Chemical Composition (%)					Mechanical Properties	
%C	%Si	%Mn	%P	%S	Yield Strength (MPa)	Tensile Strength (MPa)
0.27	0.40	1.20	0.04	0.05	235	402

Table 2

Chemical composition and mechanical properties of the AWS E7018 filler metal [1]

Chemical Composition (%)			Mechanical Properties	
%C	%Si	%Mn	Yield Strength (MPa)	Tensile Strength (MPa)
0.08	1.50	1.26	437	470

Table 3

Welding parameters used for the SMAW process [1]

.Parameter	Value
Electrode	AWS E7018
Diameter (mm)	3.2
Voltage (V)	25
Current (A)	100
Travel Speed (mm/min)	101.6
Heat Input (kJ/mm)	1.48

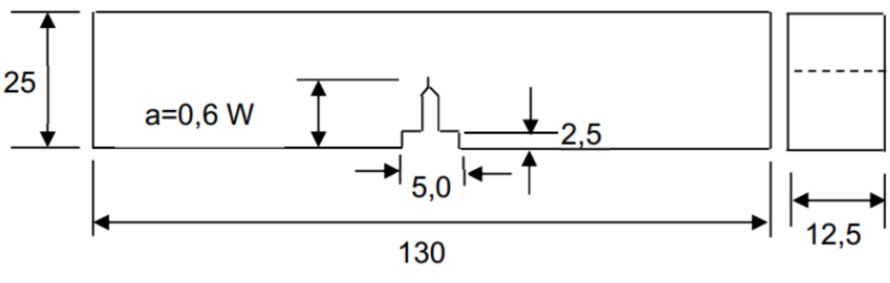
3.3 FRACTURE TOUGHNESS TESTING

The core of the experimental work was the fracture toughness tests, conducted according to the ASTM E1820 standard [5].

- Specimen Preparation: Three Single Edge Notched Bend (SENB) specimens were extracted for each zone of interest (BM, HAZ, FZ), as shown in Figure 1.
- Fatigue Pre-cracking: All specimens were pre-cracked by fatigue to achieve a sharp crack front with a crack length-to-width ratio (a/W) of approximately 0.6.
- J-R Curve Testing: The fracture tests were performed using the single-specimen elastic compliance technique. This method was chosen because it is widely accepted and significantly reduces the cost and time of testing by requiring fewer specimens [1]. It involves applying successive partial unloading to monitor the stable crack growth (Δa) throughout the test.

Figure 1

Geometry of the SENB fracture toughness specimens (dimensions in mm) [1]



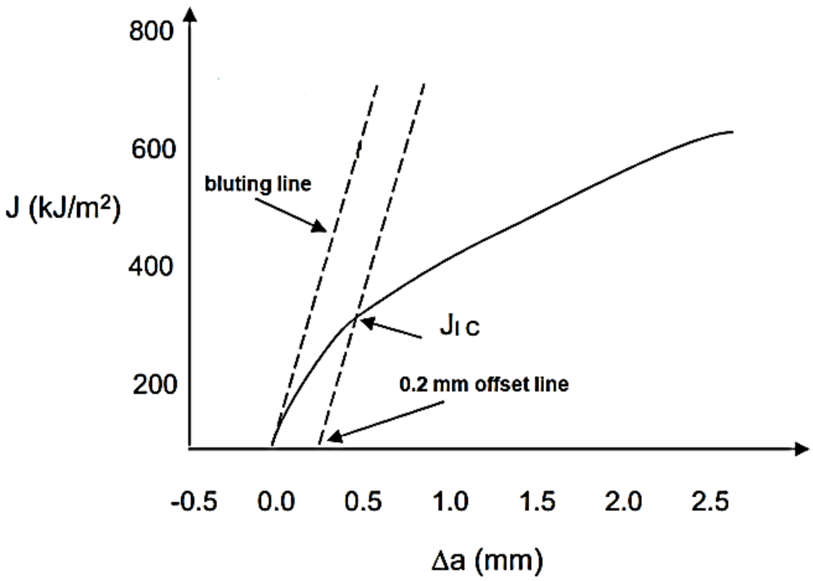
- Fatigue Pre-cracking: All specimens were pre-cracked by fatigue to achieve a sharp crack front with a crack length-to-width ratio (a/W) of approximately 0.6.
- a J-R Curve Testing: The fracture tests were performed using the single-specimen elastic compliance technique. This method was chosen because it is widely accepted and significantly reduces the cost and time of testing by requiring fewer specimens [1]. It involves applying successive partial unloading to monitor the stable crack growth (Δa) throughout the test.

INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

- Determination of J_{Ic} and $CTOD_{Ic}$: The J-integral was calculated at each unloading point to generate a J-R curve, from which the critical fracture toughness value, J_{Ic}, was determined according to the ASTM E1820 procedure (Figure 2). The critical CTOD value, $CTOD_{Ic}$, was then calculated from J_{Ic} using the relationship described in Section 2.2.2.

Figure 2

Schematic of the J-R curve for determining JIc as per ASTM E1820 [5]



4 RESULTS AND DISCUSSION

4.1 MICROSTRUCTURAL ANALYSIS

The base metal (BM) exhibited a typical ferrite-pearlite structure. The fusion zone (FZ) was primarily composed of fine-grained acicular ferrite, which is known for its high toughness. The heat-affected zone (HAZ) showed significant changes, including

a coarse-grained region (CGHAZ) near the fusion line containing bainitic structures, a result of the rapid cooling associated with the low heat input welding process [1].

4.2 TENSILE AND HARDNESS PROPERTIES

As shown in Table 4, the welded joint exhibited higher strength but lower ductility than the base metal. Hardness was highest in the FZ, followed by the HAZ, and then the BM.

INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

Table 4

Average mechanical properties of the base metal and the welded joint [1]

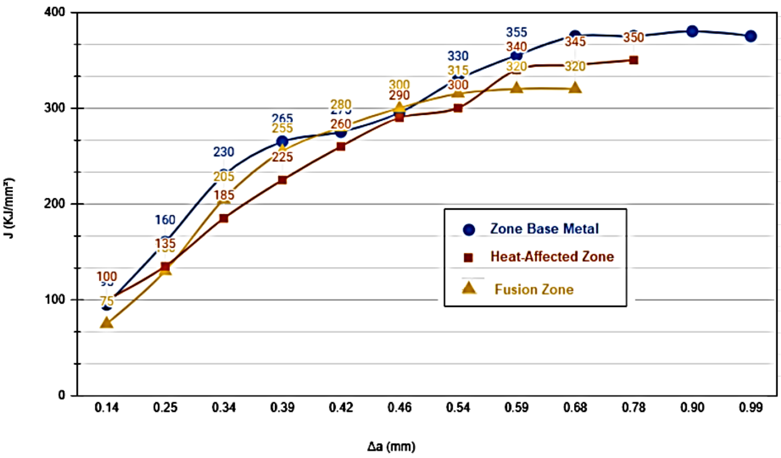
Property	Welded Joint (ASTM A36+E7018)	Base Metal (ASTM A36)
Yield Strength, σy [MPa]	424.13	249.62
Tensile Strength, σu [MPa]	483.53	413.49
Elongation [%]	20.98	33.87

4.3 FRACTURE TOUGHNESS RESULTS

The experimental J-R curves are presented in Figure 3. From these curves, the critical fracture toughness values, JIc and CT ODIc, were determined. The average values for each zone are summarized in Tables 5 and 6. The results clearly indicate that the HAZ possesses the lowest fracture toughness.

Figure 3

Experimental J-R curves for the different zones of the welded joint: Base Metal (BM), Heat-Affected Zone (HAZ), and Fusion Zone (FZ). Trend lines have been added for each data series to visualize the fracture toughness progression. The J-Integral values for each experimental point are indicated directly on the graph for added clarity. [1].



4.4 DISCUSSION

The experimental results consistently show that the HAZ is the most critical region in the welded joint in terms of fracture toughness. The superior toughness of the fusion zone (J_{Ic} = 325.32 kJ/m^2) is attributed to its fine-grained acicular ferrite microstructure, which creates a highly tortuous path for crack propagation.

Table 5

Average J_{Ic} values for the different zones [1]

Zone	J_{Ic} (kJ/m^2)
Base Metal (BM)	320.48
Heat-Affected Zone (HAZ)	318.71
Fusion Zone (FZ)	325.32

Table 6

Average $CTOD_{Ic}$ values for the different zones [1]

Zone	$CTOD_{Ic}$ (mm)
Base Metal (BM)	0.55
Heat-Affected Zone (HAZ)	0.40
Fusion Zone (FZ)	0.57

Conversely, the lower toughness of the HAZ (JIc = 318.71 kJ/m2) is a direct consequence of adverse microstructural transformations. The coarse-grained structure in the CGHAZ provides a lower-energy path for a crack to follow. Furthermore, the low heat input and lack of preheating led to high cooling rates, promoting the formation of brittle microconstituents like lower bainite. This finding is consistent with recent studies, which have demonstrated that such thermal cycles in low-carbon steels promote the formation of hard, low-toughness phases in the coarse-grained region, acting as preferential sites for cleavage initiation [16, 18].

4.5 FRACTOGRAPHIC ANALYSIS

Analysis of the fracture surfaces of the SENB specimens provides further insight into the fracture mechanisms. The fracture surfaces of the “Base Metal (BM)” and the “Fusion Zone (FZ)” specimens were predominantly characterized by ductile microvoid coalescence (dimples), consistent with their higher toughness values. In stark contrast, the fracture surface of the “Heat-Affected Zone (HAZ)” specimen revealed a mixed-mode fracture, with significant areas exhibiting brittle features like quasi-cleavage facets. This confirms the detrimental influence of the coarse-grained microstructure and brittle phases, identifying the HAZ as the most probable site for fracture initiation.

5 CONCLUSIONS

Based on the experimental investigation, the following conclusions can be drawn:

INTERNATIONAL SEVEN JOURNAL
OF MULTIDISCIPLINARY
ISSN: 2764-9547

1. The elastic compliance technique proved to be an effective and efficient method for generating precise J-R curve data for the weldment.
2. The heat-affected zone (HAZ) was unequivocally identified as the region with the lowest fracture toughness (J_{Ic} = 318.71 kJ/m^2, CT OD_{Ic} = 0.40 mm), making it the most critical area for fracture initiation.
3. The variation in fracture toughness is directly attributable to microstructure. The superior toughness of the FZ is due to its fine acicular ferrite. The poor toughness of the HAZ is a consequence of the coarse-grained structure and the formation of brittle phases near the fusion line.

Practical Implications

- Limit heat input to < 1.5 kJ/mm to minimize HAZ grain growth
- Consider post-weld heat treatment for critical applications
- Monitor cooling rates between $800 - 500^{\circ}C$ to avoid bainite formation

6 FUTURE WORK AND RECOMMENDATIONS

Based on the findings of this study, several avenues for future research are recommended to further enhance the understanding and safety of welded structures:

1. Influence of Initial Crack Size: Conduct a systematic study to analyze the influence of the initial crack length (a_0) on the calculated J-integral values. This would help to verify the independence of the material's J-R curve from the initial crack size within the valid ASTM limits.
2. a Effect of Temperature: Investigate the fracture behavior of the welded joint at different temperatures, particularly at lower service temperatures. This would allow for the determination of the ductile-to-brittle transition temperature (DBTT) for each zone (BM, FZ, and HAZ), which is critical for applications in colder environments.
3. Influence of Specimen Geometry: Evaluate the effect of specimen geometry and thickness on the fracture toughness behavior and the constraint conditions at the crack tip. Comparing results from different specimen types (e.g., Compact Tension vs. SENB) could provide valuable insights into how geometry affects the measured toughness values.

REFERENCES

Anderson, T. L. (1991). Fracture mechanics: Fundamentals and applications. CRC Press.

ASTM International. (1995). E813-87: Standard test method for JIc, a measure of fracture toughness. In Annual book of ASTM standards (Vol. 03.01). ASTM International.

ASTM International. (1997). E8M-97: Standard test method for tension testing of metallic materials. In Annual book of ASTM standards (Vol. 03.01). ASTM International.

ASTM International. (1999). E1820-99: Standard test method for measurement of fracture toughness. In Annual book of ASTM standards (Vol. 03.01). ASTM International.

Belzunce, F. J., & Viña, J. A. (2000). Fundamentos de ciencia de los materiales. Universidad de Oviedo.

Broek, D. (1994). The practical use of fracture mechanics. Fracture Research Inc.

Callister, W. D. (1995). Ciencia e ingeniería de los materiales (Tomo 1, 1.ª ed.). Editorial Reverté.

Chapetti, M. D., et al. (2018). A simple expression to estimate the fatigue endurance of welded joints. MATEC Web of Conferences, 165, Article 05001. https://doi.org/10.1051/matecconf/201816505001

Correia, J., et al. (2020). Experimental and numerical investigation on the fracture toughness of welded joints of S355 structural steel using J-integral and CTOD. Engineering Failure Analysis, 118, Article 104886. https://doi.org/10.1016/j.engfailanal.2020.104886

Das, A., et al. (2020). A review on the role of microstructure on the toughness of heat-affected zones in welded steels. Welding in the World, 64, 855–871. https://doi.org/10.1007/s40194-020-00874-y

Electric Power Research Institute. (1992). Fundamentos de mecánica a la fractura: Su aplicación a la industria nuclear. Electric Power Research Institute.

Herrera, R. (1996). Mecánica de fractura elasto-plástico: Aplicaciones a uniones soldadas [Tesis doctoral, Universidad Nacional de Mar del Plata].

Ipohorski, M., & Acuña, R. J. (1988). Fractografía: Aplicaciones al análisis de fallas [Informe]. Comisión Nacional de Energía Atómica.

Kumar, S., & Shahi, A. S. (2019). J-R curve evaluation and fracture behavior of dissimilar welded joints between carbon and stainless steel. Journal of Manufacturing Processes, 45, 10–23. https://doi.org/10.1016/j.jmapro.2019.06.027

Lan, L., et al. (2022). Correlation between microstructure, mechanical properties, and fracture toughness of the simulated coarse-grained heat-affected zone of a high-strength steel. Materials Science and Engineering: A, 832, Article 142491. https://doi.org/10.1016/j.msea.2021.142491

Pérez Ipiña, J. (1995). Curso especializado tópicos de mecánica de fractura. Universidad del Comahue.

Poursalehi, R., & Zangeneh, Sh. (2021). Influence of welding heat input on microstructure and toughness of coarse grain heat-affected zone in high-strength low-alloy steels. Journal of Materials Research and Technology, 15, 433–446. https://doi.org/10.1016/j.jmrt.2021.08.056

Saha, A., et al. (2019). Effect of heat input on the microstructure and mechanical properties of SMAW welded ASTM A36 steel joints. Materials Today: Proceedings, 18, 4879–4886. https://doi.org/10.1016/j.matpr.2019.07.479

Taplin, D. M. R., et al. (2011). The World Academy of Structural Integrity, retrospective and prospective. Strength, Fracture and Complexity, 7(2), 85–119. https://doi.org/10.3233/SFC-2011-0112

Tosal, L. (2000). Influencia de la geometría de la probeta y de la velocidad de deformación en la transición dúctil-frágil del acero microaleado AE-460 [Tesis doctoral, Universidad de Oviedo].