Numerical simulation of the fracture behavior of aluminum alloy welds: Al6061-T6

Ali Benhamena / Laboratoire LPQ3M, Université de Mascara, Algérie
ali_benhamena@yahoo.fr

Laid Aminallah / Département des sciences et techniques, Université de Mascara, Algérie

Abdelghani Baltach / Laboratoire LPQ3M, Université de Mascara, Algérie baltachabdelghani@yahoo.fr

Mohamed Benguediab / Département de génie mécanique, Université de Sidi Bel Abbes, Algérie

Abdelkrim Aid / Laboratoire LPQ3M, Université de Mascara, Algérie

***Abstract*—Welding is used to realize permanent assembly in mechanical structures to assure the continuity of the parts to be assembled contrary to the other assembly techniques which have physical or chemical discontinuities. Generally, crack evolution depends on several intrinsic and extrinsic parameters of material. The aim of this work is to analyze the severity of crack defects on the mechanical behavior of Welded joints. The cracks are considered located in the weld metal. The J-integral method was used to analyze the fracture behavior of these structures by the two-dimensional finite element method using Cast3M code. The effect of the mechanical properties, the mismatching and the crack size on the J-integral values was highlighted. A good correlation between the FEM simulations and the literature analysis results was observed. We note that the loading mode affects directly the J-integral value and consequently on the mechanical behavior of the welded joint.**

***Key words*—J-integral, welding, fracture, plastic behavior, finite element analysis.**

I. Introduction

Welded structures always contain inherent defects even when no errors are made in selecting the correct combination of materials, joint design or welding processes [1, 2]. For example, when fusion welding is employed in fabrication, the highly non-uniform temperature field near the weld pool introduces large plastic strains in the solidified weld metal and in the heat-affected zone (HAZ) [3]. Further, a variety of problems are often developed by the expansion and shrinkage at and near the weld pass, in addition to the general constraints introduced by the rest of the structure. As a consequence, residual stresses of considerable magnitude in level with material yield strength are a common feature in these narrow weld regions. Apart from the presence of various defects, the inhomogeneous material composition producing a non-uniform deformation field naturally complicates the predictions of material reliability of the resulting weld-base metal composite. Therefore, for many engineering applications, particularly in nuclear systems, the more appropriate fracture mechanics techniques are imperative for obtaining the material crack growth resistance parameter [4]. As a parameter characterizing crack tip field, the J integral has played an important part in elastic-plastic fracture mechanics and assessment of homogenous structure [5, 7]. When J -integral concept is used in welded joints, the situation is much more complicated due to the existence of mechanical heterogeneity. In the majority of case, the weldment is thought of as made of only one material – all weld or base metal, the performance difference between weld and base metal is not taken into account [8, 9]. Sham [10] and Lee [11] found that the mismatch in yield strengths alters crack tip stress fields (triaxialities), which in turn can affect the fracture toughness of biomaterial joints. Such mismatch induced constraint effects are in contrast to the constraint effect for homogeneous specimens induced by geometry and the loading mode. Recently, many studies [12] on the evaluation of the fracture toughness have been published for weldment where the crack is located in the zone of weld metal. However, only few or no studies have focused on the fracture of weldment under loading of mixed mode. Nevertheless the influences of mismatching ratio and the loading mode on the fracture behaviour of welded joint remain unclear subject. These facts lead the authors to focus of the current study, in order to contribute in this way. In the linear elastic fracture mechanics (LEFM), the stress intensity factor (K) may be used as a parameter to define the severity of the crack tip on the fracture behaviour of the structure can be easily reflected by superposition [13]. However, outside the LEFM K is no longer applicable and an appropriate elastic–plastic parameter must be used. Although, in many cases, the J-integral is adopted as the elastic plastic fracture parameter [14]. Many authors [15] were used the finite element method (FEM) which is an important tool to design a practical mechanical component, such as the welded joints. In this paper, the FEM based on the computation of the J integral at the crack front was used to analyze the defect severity in order to study the fracture behaviour of welded joint. Finally, the numerical results were discussed and some conclusions are given.

II. J INTEGRAL AND MISMATCHING

A. J integral evaluation

The present study employs the domain-integral approach, as originally developed by Shih [16] to compute the energy release rate along the crack front.

$$J(s) = \lim_{\Gamma \to 0} \int_{\Gamma} \left[(W+T)\, n_1 - P_{Ji} \frac{\partial u_i}{\partial X_1} n_j \right] d\Gamma \quad (1)$$

Where W and T are the stress work density and the kinetic energy density per unit volume at t = 0; Γ is a vanishingly small contour which lies in the principal normal plane at s, and nj is the unit vector normal to Γ. Pji denotes the non symmetric 1st Piola−Kirchhoff (1st PK) stress tensor which is work conjugate to the displacement gradient expressed on the t = 0 configuration, $\partial u_i / \partial X_j$, i.e., the stress work rate is simply $P_{ij}\, \partial u_i / \partial X_j$ per unit volume at t = 0. All field quantities are expressed in the local orthogonal coordinate system, X1-X2, at location s on the crack front.

ASTM E-1820 determines the material fracture toughness JIc based on the intersection between the J–R curve and a 0.2 mm offset of the construction line, which follows:

$$\begin{cases} J = 2\,\sigma_y\, \Delta a \\ \Delta a = a_f - a_i \end{cases} \quad (2)$$

σ_y : yield stress, a_f : current crack depth and a_i : initial crack depth.

From the J_{Ic}, one can calculate a fictive value of K_{Ic}, called K_J according to Labbens [31]:

$$k_j = \sqrt{\frac{E\, J_{Ic}}{1-\upsilon^2}} \quad (3)$$

B. Mismatching

In this paper, two-dimensional plane strain, finite element analyses using the J integral method are conducted for modelling the crack growth in a mis-matched specimen, Fig. 1. A crack is assumed to be located in the center line of the weld. Moreover, the interfaces between the weld metal and the base metal are assumed to be perfectly bonded, so that depending along the interface cannot occur. It is assumed that crack growth occurs along the center line of the weld. Throughout this paper, attention is concentrated on such idealized bi-material weld with a mismatch in strength, such that the yield strength of the weld metal (σyMW), differs from the base metal yield strength (σyMB). The difference in the strength level is quantified by the so-called mis-match ratio.

$$M = \frac{\sigma_{yMF}}{\sigma_{yMB}} \quad (4)$$

With M > 1 referring to as overmatching, M < 1 as undermatching and M = 1 as matching.

III. GEOMETRICAL AND MATERIALS MODELS

A number of typical crack specimens with unit thickness are adopted in our numerical tests. They include:

- TPCB (SENB): the three-point cracked beam bending specimen with concentrated load P, Fig. 1a;
- CCP1: the center cracked panel under overture mode loading (mode I), Fig. 1b;
- CCP2: the center cracked panel under mixed mode loading (mode I/II), Fig. 1c

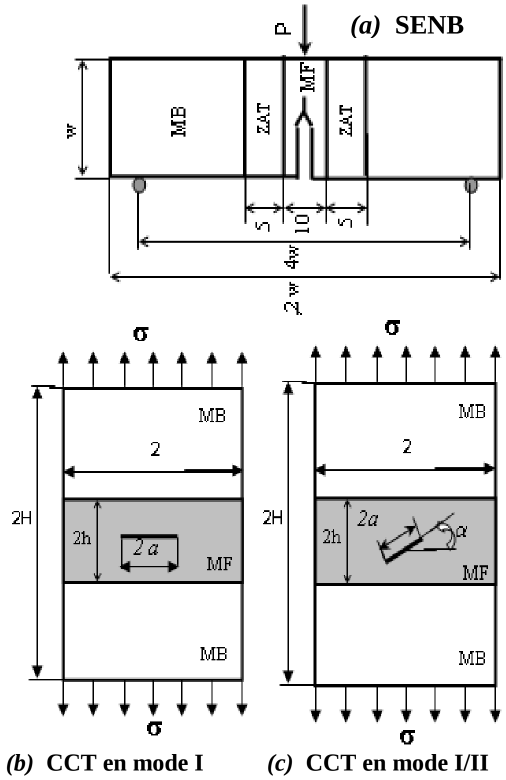

Fig. 1. Schematic models analyzed: (a) TPCB (SENB); (b) CCP1 and (c) CCP2

All behaviors of the materials used in this study were assumed to follow a Ramberg–Osgood law:

$$\begin{cases} \varepsilon &= \varepsilon_e + \varepsilon_p \\ \varepsilon &= \dfrac{\sigma}{E} + \left(\dfrac{\sigma}{H}\right)^{1/n} \end{cases} \quad (5)$$

The typical uniaxial stress–strain curve of this material at room temperature is given in Fig. 2. Full details of the behavior law of this steel are given elsewhere [17].

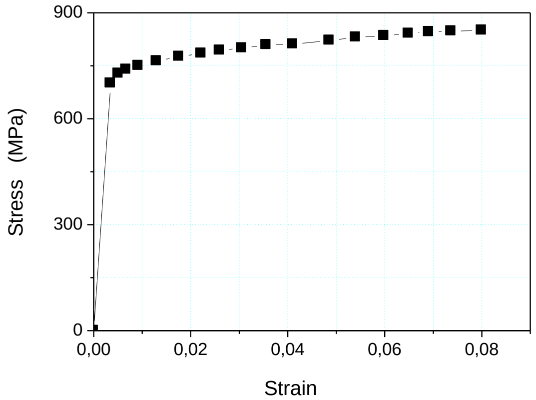

Fig. 2. Uniaxial stress–strain curve of the steel at room temperature [17].

IV. Finite Element Modeling

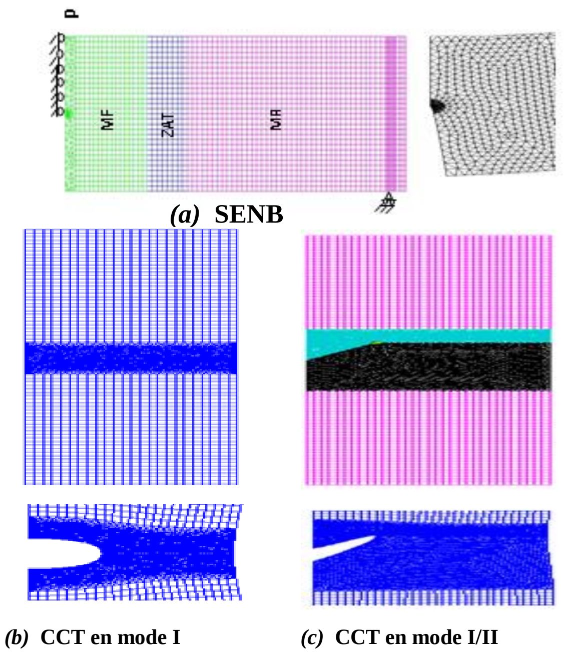

Fig. 3. Finite element discretisation scheme: global view and zoomed view near the crack tip

Fracture mechanics aims to determine the effect of any cracks on the mechanical behavior of structures. The problems of cracked of the welded joint are more complicated than the cracked problems of the homogenous materials. Because, the stress field at the tip of the crack greatly depend on the mechanical behavior of materials. Computational methods such as finite element method are widely accepted in pipe-lines and a welded joint [18] as an important tool used to investigate the fracture of these structures. Contributing to this field, we analyzed the fracture behavior of welded joint by the computation of J integral at the crack front. Finite element simulation was done using Cast3M code [19] (elastic-plastic fracture mechanics). Fig. 3 shows the finite element mesh. Taken into account the symmetry of loading and geometry, only the half of the model is studied in order to reduce the calculation time. Quadratic elements (height-node) are used in the modeling. The singularity at the near of the crack is modeled by special elements in order to increase the precision of calculation. The theory of incremental plasticity is introduced to model the material nonlinearity. The iterative method of Newton-Raphson is used as an approach to solve nonlinear equations by finite elements.

V. Results and Discussions

A. Validation of the finite element analysis (case of SENB specimen)

The crack behavior is analyzed by computing the J integral at the crack front of welded joint. For the first step, it is necessary to validate the J-integral solutions for SENB specimen; a number of finite element analyses (FEA) was performed initially for one case taken from the past work of Rodrigues [17]. Fig. 4 show the variation of the J integral as a function of imposed displacement for the geometrical crack configurations conducted for this study.

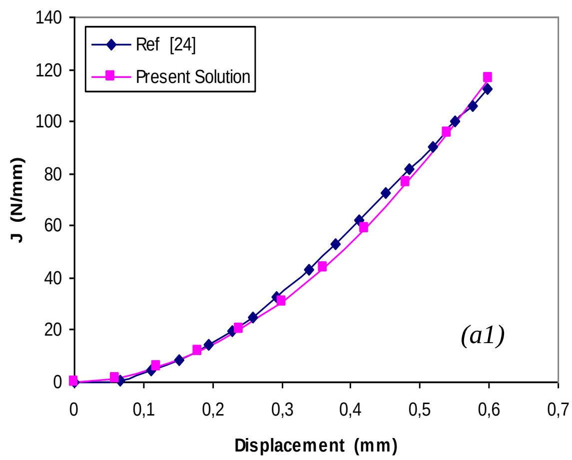

Fig. 4. Curve J-Displacement for (a/w=0,5)

A first observation from the reading of Fig. 4 is that the J integral increases proportionally with the increasing of the imposed displacement (applied load). However, in this configuration of crack size of welded joint it was found that under lower applied load (imposed displacement < 0.2mm), the J-integral increases significantly with the increasing of the applied load, while under higher applied load (imposed displacement > 0.2mm), the J-integral increases sharply with respect to the crack size. Fig. 4 shows also, the comparisons of J integral versus imposed displacement plots from the present study with the corresponding finite element results generated by Rodrigues [17]. The two sets of results are in close agreement with each other.

To study the effect of loading on the behaviour fracture of the welded joint (J integral), we plotted the curve in Fig. 5 which illustrate the evolution of J integral versus the loading, these results show that the rate of increase of the J integral is more important when the loading exceeds 300MPa. This phenomena can be attributed for the value of applied load under which the plastic strain is absent for value of loading lower at limit load (elastic region); the stress level around the crack is lower than the yield strength of steel used in the present work. We noticed, however, that for higher loading (P > 300 MPa) the level of stresses near the crack tip is higher than the yield strength which cause plastic strains (plastic region), with the magnitude of plastic strain governing the evolution of J integral. Beyond the limit load, the increasing rate of J integral has an exponential form versus loading. This behavior was confirmed numerically by other authors [11, 12]

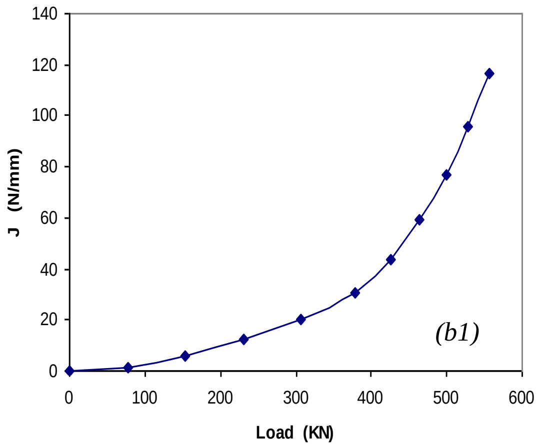

Fig. 5. Curve J- Applied load for (a/w=0,5)

B. Central Crack in Tension CCT

For this example, the study focuses on a CCT configuration (Fig. 1) to examine the opening mode (mode I) and mixed mode (mode I / II)) to evaluate the J integral for the study of a welded joint formed by the base metal and weld metal. We present in this section a numerical calculation based on the J integral concept for the study of a welded joint. The material Law behavior used is a power law, Eq. (5). Table 1 Recall the mechanical properties of the material (WF and BM) considered for this joint. The loading is simulated by imposing, on the opposite edge in terms of the crack (Fig. 1), an incremental displacement in steps of 0.1 mm.

We presented in this section the J integral normalized by the JIc evaluated from the equation (3) according to Labbens [20]:

TABLE I. PARAMETER VALUES OF THE POWER LAW DESCRIBING THE MATERIALS CONSIDERED (BM, WM) [21]

Materials	Mechanical properties				
	E (GPa)	R_e *(MPa)*	R_m *(MPa)*	*H*	*n*
6061-T6	68	276	310	403	0.07
As-welded	68	120	182	312	0.18

B.1 Opening mode (mode I)

The two-dimensional numerical study was performed with two configurations (BM and WM). In Fig. 6 we represent the evolution of the J integral as a function of imposed displacement. From the results shown in Fig. 6, we can deduce the following conclusions: the evolution of the integral J is plotted for a displacement reached a value of 0.4 mm for the base metal (BM) and weld metal WM) for a crack length equal to 4 mm (*a = 4. mm*).

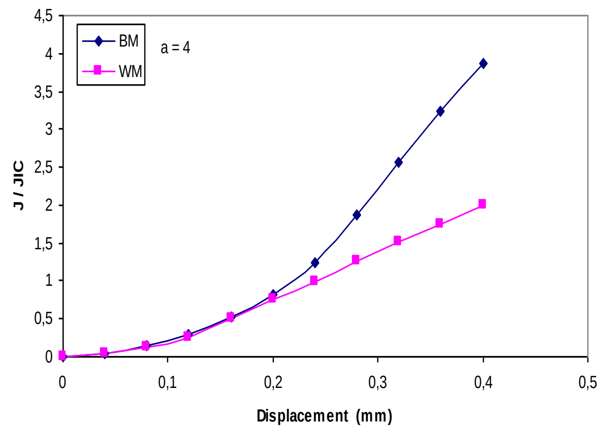

Fig. 6. Curve J-Displacement for (a/w=0,25)

These results clearly show that when the properties of material ductility are important, the evolution of the integral J versus load (imposed displacement) is important. This is explained by the fact that the extension of a ductile material (case of BM) is higher than that of a brittle material (WM) because of the effect of the heat of the welding process.

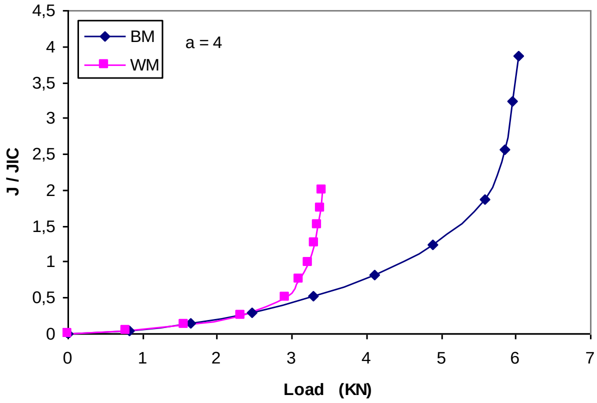

Fig. 7. Curve J- Applied load for (a/w=0,25)

We can also determine the evolution of the J integral as a function of loading (Fig. 7). We note first that the evolution of the J integral versus load is almost similar to that shown in Fig. 5 (case of the SENB specimen). This behavior was confirmed analytically and numerically by other authors [7, 9, 17]. We observe also a similar results for a crack length equal to 8 mm, *(*Fig. 8 and Fig. 9 for case of crack length a = 8. mm*)*.

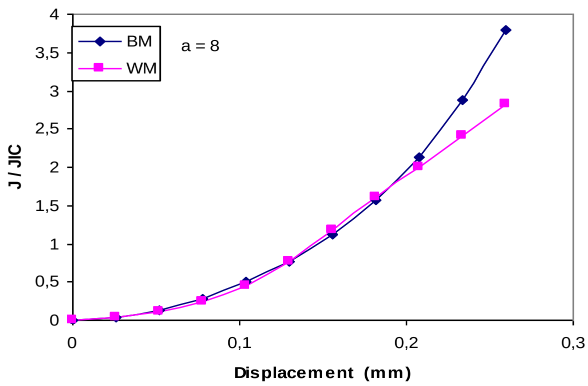

Fig. 8. Curve J-Displacement for (a/w=0,5)

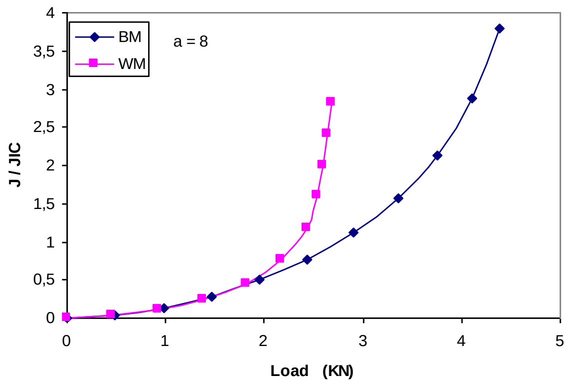

Fig. 9. Curve J- Applied load for (a/w=0,5)

B.2 Mixed mode (Mode I/II)

In this section we discussed the influence of failure mode on the evolution of the J integral for the study of a welded joint. Fig. 10 shows the effect of failure mode (angle variation) on the evolution of the J integral versus imposed displacement, or loading Fig. 11 for the two configurations studied (BM and WM).

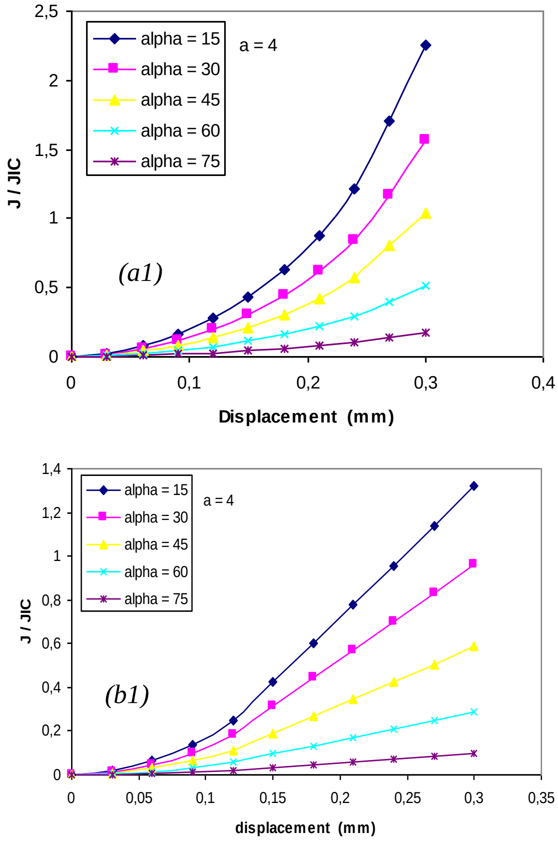

Fig. 10. Curve J-Displacement for (a/w=0,25), (a1) BM, (b1) WM

We note that whatever the material study the effect of the angle variation is negligible for low values of loading and the opposite effect is observed for high load values. However, we note that the failure mode effect (angle variation) can be ignored in the elastic regime (i.e. level of the stress at the near of the crack is lower). For the elastic plastic regime, the crack angle inclination has a predominant effect on the J integral evolution to study the behavior of a welded joint (i.e. level of the stress at the near of the crack is higher).

VI. Conclusions

This study was carried out in order to analyze the effect of the mechanical properties and mode loading on the mechanical behavior of an aluminum alloy welds. The obtained results allow us to deduce the following conclusions:

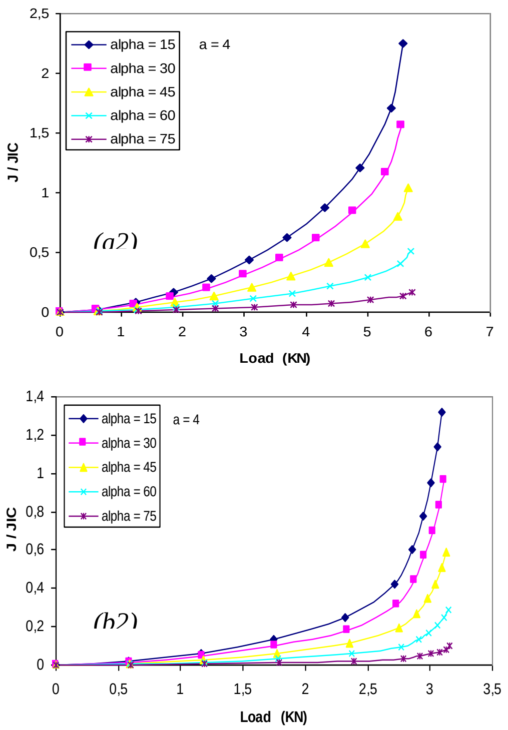

Fig. 11. Curve J- Applied load for (a/w=0,25), (a2) BM, (b2) WM

- For the open mode (mode I), the values of the integral J are higher than those for the mixed mode (mode I/II).
- The crack direction (angle variation) has a predominant effect on the J integral for the study of a welded joint.
- Whatever the mode of failure, the J integral is strongly influenced by the material properties.
- The effect of mode of failure can be ignored in the elastic regime and the opposite effect is marked for the elastic plastic regime. We can conclude that the parameters of ductility of a material (hardening curve) play an important role for studying the fracture behavior of a weld

References

[1] Meric C., Tokdemir M., An Investigation of the Weld Region of the SAE 1020 Joined with Metal Active Gas and Determination of the Mismatch Factor. ASM International. JMEPEG 1999; 8:601-605

[2] Bose Filho W.W.,. Carvalho A.L.M, Bowen P. Micromechanisms of cleavage fracture initiation from inclusions in ferritic welds. Part II. Quantification of local fracture behaviour observed in fatigue pre-cracked test pieces. Materials Science and Engineering A 2007; 452–453: 401–410

[3] BISWAS K. Notch tip deformation and J-integral analysis for implant weldability test specimen. International Journal of Fracture 1994; 67:99-116.

[4] Mersida M., Bojan M., Ljubica M., Marko R., Zijah B., Aleksandar S., Analysis of welded tensile plates with a surface notch in the weld metal and heat affected zone. Engineering Fracture Mechanics 2010; 77: 2958–2970.

[5] Hyungyil Lee, Jinyoung Cho, Overload analysis and fatigue life prediction of spot-welded specimens using an effective J-integral, Mechanics of Materials, 2005, 37, 19-32.

[6] Hyungyil L., Yun-Jae K. Interfacial crack-tip constraints and J-integral for bi-materials with plastic hardening mismatch. Int J Fract 2007; 143:231-243.

[7] Jianqing F., Yaowu S., Mechanical heterogeneity and validity of J-dominance in welded Joints. International Journal of Fracture 2000;106: 311-320.

[8] Boothman DP, Lee MMK, Luxmoore AR, The effects of weld mismatch on J-integrals and Q-values for semi-elliptical surface flaws. Engineering Fracture Mechanics 64; 1999: 433-458.

[9] Burstow MC, Howard IC, Ainsworth RA, The effect of material strength mismatching on constraint at the limit load of welded three-point-bend specimens, International Journal of Fracture 1998; 89: 117-142.

[10] ShamTL, Li J, Hancoc k J W, A family of plane strain crack tip stress fields for interface cracks in strength mismatched elastic-perfectly plastic solids. J Mech Phys Solids 1999; 47: 1963-2010.

[11] Lee H, Kim YJ, Interfacial crack-tip constraints and J-integrals in plastically mismatched bi-materials. Eng Frac Mech 2001; 68: 1013-1031.

[12] Lei Y, Ainsworth RA, The estimation of J in three-point-bend specimens with a crack in a mismatched weld, International Journal of Pressure Vessels and Piping 1997; 70: 247-257.

[13] Anderson TL, Fracture mechanics fundamentals and applications, CRC Press, 1995.

[14] Rice JR, J. Appl. Mech. 1968; 35: 379-386.

[15] Jiang WC, Wang BY, Gong JM, Tu ST, Finite element analysis of the effect of welding heat input and layer number on residual stress in repair welds for a stainless steel clad plate, Materials & Design, 2011; 32: 2851-2857.

[16] Rice JR, A path-independent integral and approximate analysis of strain concentration at notches and cracks, J. Appl. Mech.,1968; 34: 379-386.

[17] Rodrigues DM, Menezes LF, A. Loureiro The influence of the HAZ softening on the mechanical behaviour of welded joints containing cracks in the weld metal. Engineering Fracture Mechanics 2004; 71 : 2053-2064.

[18] Paolo L, Roberto T, The use of the JV parameter in welded joints: Stress analysis and fatigue assessment. International Journal of Fatigue 2009; 31:153-163.

[19] Castem (www-cast3m.cea. fr).

[20] LABBENRS. C. Introduction à la mécanique de la rupture, Pluralis, 1980.

[21] Ambriz RR, Mesmacque G, A. Benhamena, Ruiz A, Lopez VH, Amrouche A. Fatigue Crack Growth Behavior on 6061-T6 Aluminum Alloy Welds Obtained by Modified Indirect Electric Arc (MIEA). Iberian Conference on Fracture and Structural. Integrity 2010, Portugal March 2010.