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Influence of the Calibration Points on the S_{pb} Parameter Behavior

ABSTRACT: The present work studies the separability parameter S_{pb} behavior to estimate crack lengths when two or three calibration points are used. A set of precracked and blunt notched specimens with three-point bend ASTM-SE(B) geometry were prepared from three materials: AA 6061-T6 aluminum alloy with different side groove ratio, high-strength low-alloy welded steel, and 2.25Cr-1Mo steel. For each precracked specimen, initial and final crack length were measured on the crack surface. Intermediate crack lengths were determined by two methodologies: the standard elastic unloading and the S_{pb} parameter method using two and three calibration points. The S_{pb} crack lengths were very close to those estimated using the standard methodology; differences between them were less than $15\%\Delta a$, suggested as a difference limit value in ASTM E 1820-99 to alternative methods for measuring crack extension. The performance of S_{pb} parameter was evaluated using two and three calibration points. *J-R* curves were constructed. The J_{IQ} values obtained by the standard methodology and the S_{pb} method were similar.

KEYWORDS: fracture mechanics, integral J, separability property, crack length estimation

Introduction

The load separation property allows one to express the load P, applied to a notched body, as a product of two independent functions: a geometry-dependent function (including crack length) G, and another function dependent on material deformation properties, i.e., H. It is then, possible to write

$$P = G\left(\frac{a}{W}\right) \cdot H\left(\frac{v_{pl}}{W}\right) \tag{1}$$

where

a=crack length

v_{pl}=plastic component of load displacement point

W=characteristic length of the body

The separability parameter S_{pb} was first introduced by Sharobeam and Landes [1]. It was defined as the load ratio at constant displacement of two distinct cracked specimens: "p" and "b." The "p" subscript corresponds to a precracked specimen that exhibits crack growth during the test and "b" corresponds to the blunt notched specimen with constant crack length during the test.

$$S_{pb} = \left.\frac{P_p(a_p, v_{pl})}{P_b(a_b, v_{pl})}\right|_{v_{pl}} \tag{2}$$

The S_{pb} parameter at the beginning of the load displacement record, when there is no crack propagation, is constant, provided that the separation property holds. Hence, the crack length of the precracked specimen is equal to the initial crack length [1–6]. Conversely, the S_{pb} constancy identifies which points of the load displacement record have the initial crack length.

Assuming the validity of the load separability property in the crack length and displacement range, the variation of the S_{pb} parameter constancy is related to the onset of crack extension.

Independently of the crack tip conditions, it is possible to assume that the geometry function $G(a/W)$ is given by a power law [1,4]:

$$G\left(\frac{a}{W}\right) = \text{const}\left(\frac{a}{W}\right)^m \tag{3}$$

Replacing Eq 3 by Eq 2, the S_{pb} parameter at constant plastic displacement results in [5–7]

$$S_{pb} = \left.\frac{P_p(a_p, v_{pl})}{P_b(a_b, v_{pl})}\right|_{v_{pl}} = \left.\frac{G_p\left(\frac{a_p}{W}\right) \cdot H\left(\frac{v_{pl}}{W}\right)}{G_b\left(\frac{a_b}{W}\right) \cdot H\left(\frac{v_{pl}}{W}\right)}\right|_{v_{pl}} \tag{4}$$

As both specimens are made of the same material, the deformation functions ratio is equal to identity when they are determined at constant plastic displacement [5,6]. The last equation results in

Now it is possible to determine the crack length for the precracked specimen by:

$$a_p = a_b\left(S_{pb}\Big|_{v_{pl}}\right)^{1/m} = a_b\left(\left.\frac{P_p}{P_b}\right|_{v_{pl}}\right)^{1/m} \tag{6}$$

Hence, with Eq 6 the crack length for each point of the load displacement record can be estimated if the "m" parameter is known.

Calibration Points

The S_{pb} method was successfully applied [5,6] by utilizing three calibration points: the initial crack length, the final crack length, and a theoretical calibration point. When the final crack length is not available since tests could not stop from outside and hence the

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TABLE 1—*Material Properties AA 6061-T6.*

Temper	σ_u, Mpa	σ_y, MPa	Elongation % 1.6 mm	13 mm	6.25 mm	Brinell Hardness
T6	310	276	12	17	…	95
Bars 2 in. × 1 in.	306	267	…	…	13	88.5 average

specimen broken in two halves (impact experiments for instance), the S_{pb} method could still be applied using only two calibration points: the initial crack length and the theoretical calibration point.

The first calibration point is determined by the first part of the (S_{pb}, ν_{pl}) curve, where S_{pb} is constant and no crack growth has assumed to occur. It corresponds to the initial crack length and can be measured post-mortem on the crack surface of the broken specimen. A second point is *automatically* introduced by the boundary conditions imposed to Eq 6. When the precracked specimen during the test achieves the same crack length as the blunt notched specimen, they both bear the same load and the S_{pb} parameter is equal to one [5,6]; that is,

$$\begin{matrix} a_p = a_b \\ P_p = P_b \end{matrix} \; S_{pb} = \left.\frac{P_p}{P_b}\right|_{\nu} = \left(\frac{a_p}{a_b}\right)^m = 1 \qquad (7)$$

Using the calibration points and taking both members of Eq 5 logarithms, it is possible to determine the m value:

$$\log_{10}(S_{pb}) = m \log_{10}\left(\frac{a_p}{a_b}\right) \qquad (8)$$

Experimental Procedure

The sets of test records studied in this paper were determined using the following materials: AA 6061-T6 aluminum alloy [7], high-strength low-alloy (HSLA) welded steel, and 2.25Cr-1Mo ASTM 387-Gr22 steel. Tables 1–3 show the respective mechanical properties [8].

Each selected set should include one precracked specimen test record and one blunt notched specimen test record for the application of the S_{pb} method. Three precracked specimens were tested for each material. Single edge notched SE(B) [9] specimens were made for each material and loading in three-point bending mode at room temperature.

TABLE 2—*Material properties: HSLA welded joints.*

Specimens	σ_{YS}	Electrode
1, 2	449	ANSI/
3	484	AWS E-1XX18M
4, 5	544	E-10018
6	609	E-11018
7	571	E-12018
Reference (BN)	544	E-13018

TABLE 3—*Material properties 2.25Cr-1Mo.*

σ_{YS}, MPa	σ_u, MPa	Elongation
207	414	18 % (Φ=50 mm)

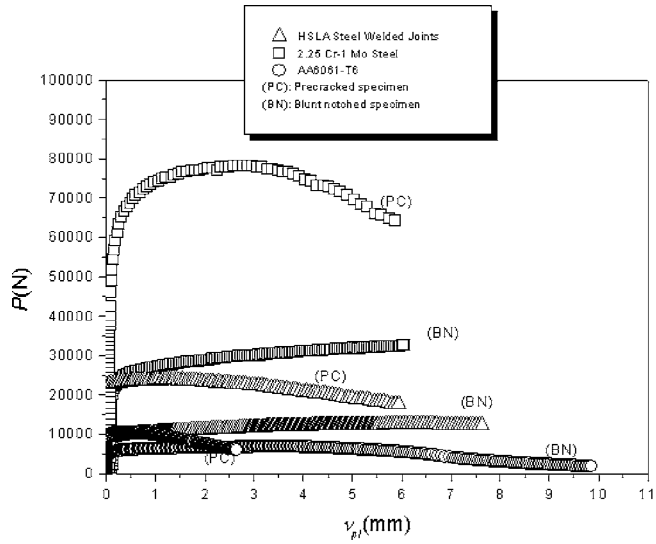

FIG. 1—*Load vs plastic displacement.*

In the case of the aluminum bars, side groove ratios were made of 8%, 16%, and 24% of B. C(T) ASTM specimens were also made with 2.25Cr-1Mo steel. These data were originally reported in Refs. [5,7]. Crack lengths were estimated by the standard elastic unloading or compliance technique and the S_{pb} methodology using two and three calibration points. Initial and final crack lengths were measured on the crack surface by means of an optical device.

Results

Load-displacement records of precracked and blunt notched specimens were obtained and reduced as follows: First, the actual compliance was calculated from the initial slopes of the load-displacement curves. The elastic displacement was then subtracted from the total displacement using the compliance measured from the test records, in order to obtain the plastic displacement as follows:

$$\nu_{pl} = \nu - P^* C;$$

where

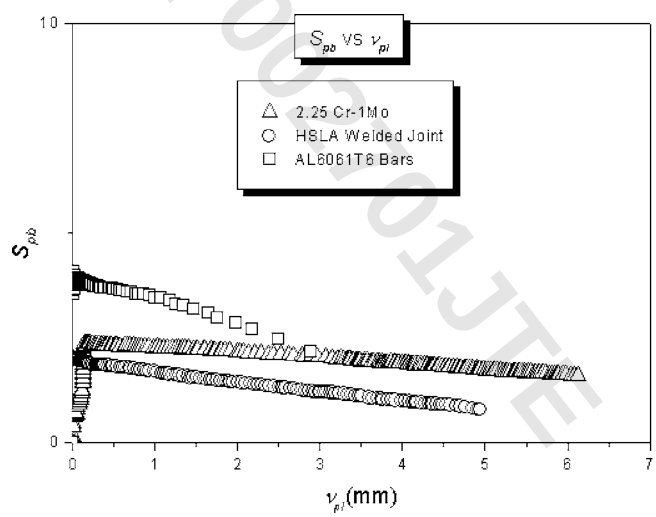

FIG. 2—*Separability parameter S_{pb} vs plastic displacement ν_{pl}.*

TABLE 4—*Results for the initial crack length AA 6061-T6.*

	Crack length, mm					Difference, mm			
Spec	SG %	Spfc (a_0)	Compl (a_{compl})	S_{pb}3p ($a_{S_{pb}3p}$)	S_{pb}2p ($a_{S_{pb}2p}$)	a_0–a_{compl}	a_0–$a_{S_{pb}3p}$	a_0–$a_{S_{pb}2p}$	Limit Value (15% Δa)
1	8	27.51	27.50	27.52	27.52	−0.01	0.01	0.03	0.52
2	16	29.65	29.64	29.64	29.66	−0.01	−0.01	0.03	0.23
3	24	28.86	28.80	28.90	28.79	0.06	−0.04	0.07	0.10

Spfc: crack length measured on the fracture superface; Compl: crack length obtained by compliance; SG: side groove.

TABLE 5—*Results for the initial crack length HSLA welded joints.*

	Crack length, mm				Difference, mm			
Spec	Spfc (a_0)	Compl (a_{compl})	S_{pb}3p ($a_{S_{pb}3p}$)	S_{pb}2p ($a_{S_{pb}2p}$)	a_0–a_{compl}	a_0–$a_{S_{pb}3p}$	a_0–$a_{S_{pb}2p}$	Limit Value (15% Δa)
1	15.37	15.40	15.39	15.36	0.03	0.02	0.01	0.42
2	15.70	15.75	15.74	15.72	0.05	0.04	0.02	0.57
3	16.52	16.47	16.49	16.50	0.05	0.03	0.02	0.46
4	15.62	15.63	15.59	15.61	0.01	0.03	0.01	0.49

Spfc: crack length measured on the fracture superface; Compl: crack length obtained by compliance.

TABLE 6—*Results for the initial crack length* 2.25Cr-1Mo *steel.*

Spec	SG %	Spfc (a_0)	Compl (a_{compl})	S_{pb}3p ($a_{S_{pb}3p}$)	S_{pb}2p ($a_{S_{pb}2p}$)	a_0–a_{compl}	a_0–$a_{S_{pb}3p}$	a_0–$a_{S_{pb}2p}$	Limit Value (15% Δa)
C(T)	0	29.86	29.91	29.89	29.87	0.05	0.03	0.01	0.59
	25	28.07	28.04	27.98	28.03	0.03	0.09	0.04	1.08
SE(B)	25	29.42	29.48	29.37	29.40	0.06	0.05	0.02	0.42

Spfc: crack length measured on the fracture superface; Compl: crack length obtained by compliance; SG: side groove.

TABLE 7—*Results for the final crack length AA 6061-T6.*

	Crack length, mm					Difference, mm			
Spec	SG %	Spfc (a_f)	Compl (a_{compl})	S_{pb}3p ($a_{S_{pb}3p}$)	S_{pb}2p ($a_{S_{pb}2p}$)	a_f–a_{compl}	a_f–$a_{S_{pb}3p}$	a_f–$a_{S_{pb}2p}$	Limit Value (15% Δa)
1	8	34.20	34.50	34.02	34.02	0.30	−0.18	0.52	0.52
2	16	37.60	37.40	37.80	37.69	−0.20	0.20	0.23	0.23
3	24	35.10	35.20	35.11	35.20	0.09	0.01	0.1	0.10

Spfc: crack length measured on the fracture superface; Compl: crack length obtained by compliance; SG: side groove.

TABLE 8—*Results for the final crack length HSLA welded joints and 2.25Cr-1Mo steels.*

	Crack length, mm				Difference, mm			
Spec	Spfc (a_0)	Compl (a_{compl})	S_{pb}3p ($a_{S_{pb}3p}$)	S_{pb}2p ($a_{S_{pb}2p}$)	a_0–a_{compl}	a_0–$a_{S_{pb}3p}$	a_0–$a_{S_{pb}2p}$	Limit Value (15% Δa)
1	18.15	18.10	18.01	18.06	0.015	0.140	0.09	0.42
2	19.55	19.55	19.45	19.53	0.000	0.100	0.02	0.57
3	19.60	19.50	19.23	19.43	0.100	0.370	0.17	0.46
4	18.89	18.90	18.67	18.87	0.010	0.220	0.02	0.49

Spfc: crack length measured on the fracture superface; Compl: crack length obtained by compliance.

TABLE 9—*Results for the final crack length AA 6061-T6.*

		Crack length, mm				Difference, mm			
Spec	SG %	Spfc (a_0)	Compl (a_{compl})	S_{pb}3p ($a_{S_{pb}3p}$)	S_{pb}2p ($a_{S_{pb}2p}$)	a_0– a_{compl}	a_0– $a_{S_{pb}3p}$	a_0– $a_{S_{pb}2p}$	Limit Value (15%Δa)
C(T)	0	33.62	33.90	33.65	33.60	0.28	0.25	0.02	0.59
	25	34.81	34.76	34.85	34.82	0.05	0.09	0.01	1.08
SE(B)	25	32.39	32.28	32.46	32.40	0.11	0.18	0.01	0.42

Spfc: crack length measured on the fracture superface; Compl: crack length obtained by compliance; SG: side groove.

TABLE 10—*J_{IQ} parameters determined from crack length estimations obtained by the studied methodologies for AA 6061-T6.*

Spec	Compl	S_{pb} 3p	S_{pb} 2p	Diff. Compl-$S_{pb}3p$, %	Diff. Compl-$S_{pb}2p$, %	Brinell (HB)
1, 8	75.98	76.39	75.82	0.53	0.74	55.10
2, 16	36.08	36.71	35.21	1.74	4.08	85.20
3, 24	27.88	26.80	26.25	3.87	2.05	88.36

Compl: compliance; $S_{pb}3p$: S_{pb} with 3 calibration points; $S_{pb}2p$: S_{pb} with 2 calibration points

TABLE 11—*J_{IQ} parameter determined from crack length estimations obtained by the studied methodologies HSLA steel welded joints.*

Spec	Compl	$S_{pb}3p$	$S_{pb}2p$	Diff. Compl-$S_{pb}3p$, %	Diff. Compl-$S_{pb}2p$, %
1	593.45	591.80	593.11	0.27	0.05
2	516.10	471.66	473.49	8.61	8.25
3	228.70	206.80	220.30	9.57	3.67
4	368.00	388.00	379.23	5.43	3.05

Compl: compliance; S_{pb}3p : S_{pb} with three calibration points; S_{pb}2p : S_{pb} with two calibration points.

P = applied load
C = initial compliance

Load versus plastic displacements curves determined are shown in Fig. 1.

The S_{pb} parameter was determined as the load ratio between a precracked and a blunt notched specimen (Eq 5; Fig. 2).

The S_{pb} parameter constant zone was determined by using +/−0.01 tolerance, which corresponds to uncertainty in initial crack length estimation of +/−0.05 mm.

The m parameter was determined by using two and three calibration points. Therefore, with the S_{pb} and m values for each specimen, the crack length for every point of the load-displacement record was obtained by utilizing Eq 6. The crack lengths were also estimated by the compliance technique used as a reference method.

A crack length estimation was considered acceptable provided that the difference between the crack lengths obtained by the S_{pb} method and those obtained by direct measurements on the fracture surface, were less than 15%Δa. This limit value was taken from the ASTM 1820-99, which establishes that the crack extension predicted by the compliance method (or other method) at the last unloading should be comparable with the measured physical crack extension, and the difference between these should not exceed 15%Δa.

The initial crack lengths obtained by S_{pb} method using two and three calibration points, by compliance methodology, and the ones measured on the fracture surface are shown in (Tables 4–6).

In all the cases the differences obtained between the S_{pb} method and the measurements made on the fracture surface were less than the value adopted as limit. The differences in the initial crack lengths obtained by the S_{pb} method using two calibration points and the ones obtained by direct measurement on the fracture surface, were in all the cases less than 0.07 mm.

The final crack lengths obtained by S_{pb} method using two and three calibration points, by compliance methodology, and the ones measured on the fracture surface are shown in (Tables 7–9).

In all the cases, the differences obtained between the S_{pb} method and the measurements made on the fracture surface were less than the value adopted as limit. The differences in the final crack lengths obtained by the S_{pb} method using two calibration points and the

TABLE 12—*J_{IQ} parameter determined from crack length estimations obtained by the studied methodologies: 2.25Cr-1Mo steel.*

Spec	SG, %	Compl	$S_{pb}3p$	$S_{pb}2p$	Diff. Compl-$S_{pb}3p$, %	Diff. Compl-$S_{pb}2p$, %
C(T)	0	179.82	182.31	177.10	1.38	1.51
	25	168.99	178.25	177.20	5.47	4.85
SE(B)	25	527.48	498.71	480.70	5.45	8.86

Compl: compliance; S_{pb}3p : S_{pb} with three calibration points; S_{pb}2p : S_{pb} with two calibration points; SG: side groove.

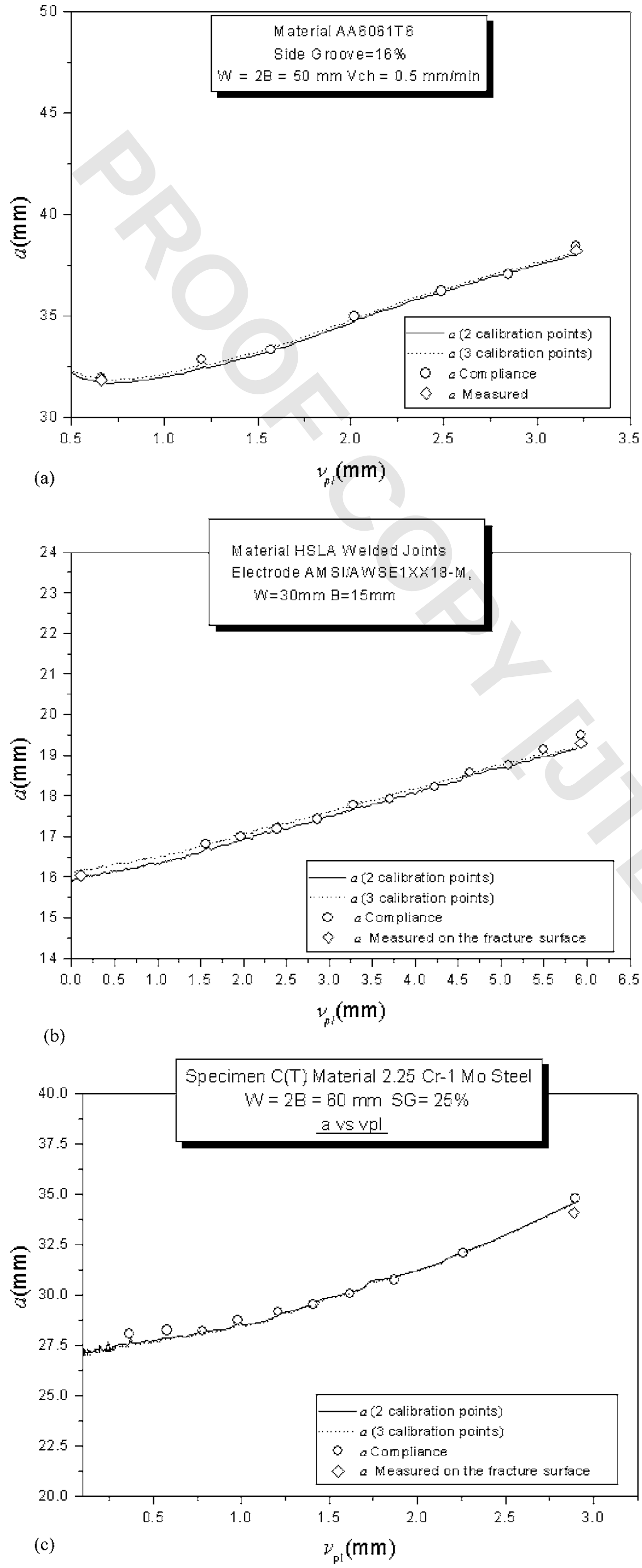

FIG. 3—*Crack length estimated by the S_{pb} method using two and three calibration points, compliance and measured on the fracture surface: (a) AA 6061-T6 bar; (b) HSLA welded joints; (c) 2.25 Cr-1Mo.*

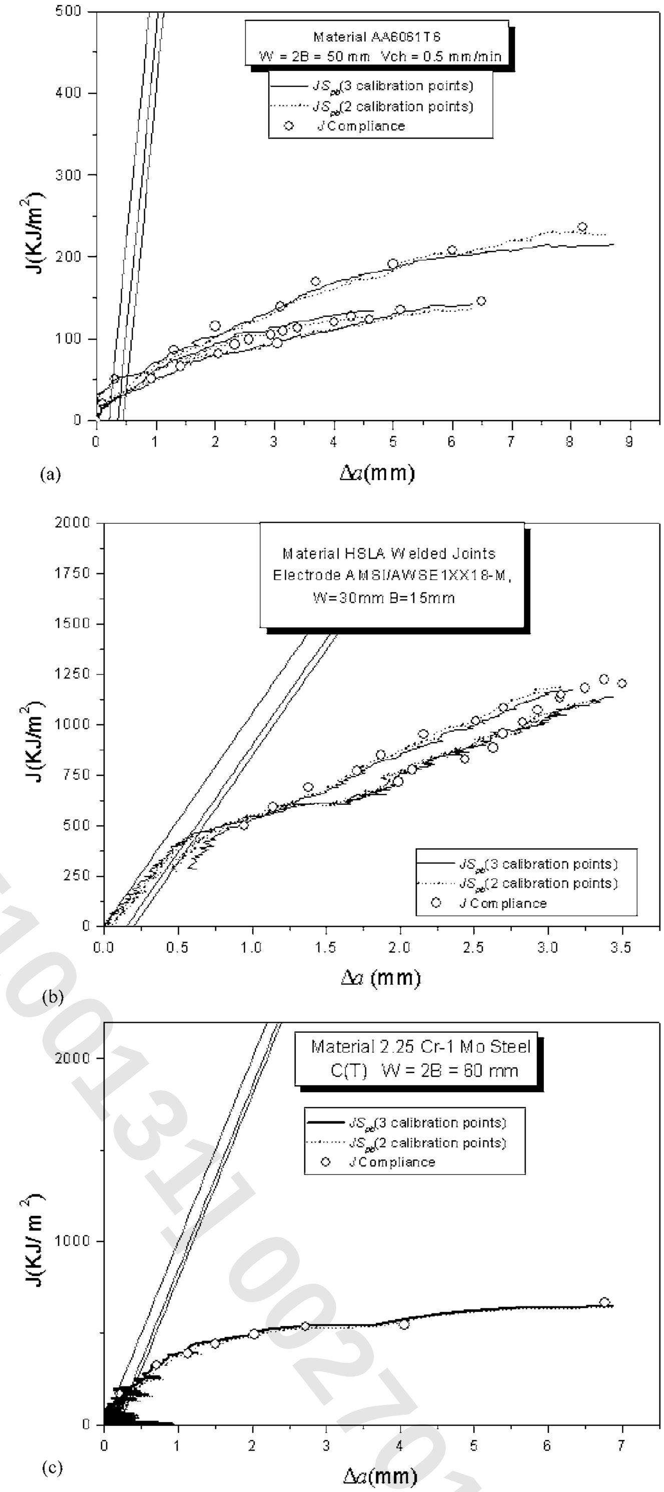

FIG. 4—*J-Δa curve, using the S_{pb} method with two and three calibration points for the crack length estimation: (a) AA 6061-T6 bar; (b) HSLA welded joints; (c) 2.25 Cr-1Mo.*

ones obtained by direct measurement on the fracture surface, were in all the cases less than 0.52 mm.

In Fig. 3, the crack lengths obtained by the S_{pb} method using two and three calibration points, the compliance method, and the crack lengths measured on the fracture surface are shown.

Crack lengths curves obtained by the S_{pb} method using two and three calibration points have almost the same shape and values as that of the compliance crack lengths. A good agreement could be seen between the S_{pb} method and the compliance method used as reference.

Using the crack length estimations, J-Δa curves were constructed and J_{IQ} parameter was determined (Fig. 4). It is possible to see in full and dashed lines the curves obtained by the crack lengths determined by the S_{pb} method with two and three calibrations points. The circles are the J values corresponding to the compliance crack lengths.

In each of the cases for each material the S_{pb}-J curves adopt the same shape of the compliance points.

The J_{IQ} parameter values obtained using the S_{pb} method were similar to those obtained by the compliance method. The J_{IQ} initiation value determined from the crack lengths obtained using the S_{pb} method with three calibration points were almost the same as those obtained by using two calibration points. The J_{IQ} initiation values are shown on (Tables 10–12). The differences between the J_{IQ} values obtained by the crack lengths determined by the S_{pb}method using two and three calibration points were less than 8.9 %.

It is possible to observe that for all materials analyzed in this work good agreement is achieved between J-Δa curves determined using, S_{pb} method with two and three calibration points, and compliance method for crack length growth estimation.

In the case of the aluminum, the J_{IQ} values decreased with increasing side groove ratio. For precracked specimens with 8 % of side grooving, a high J_{IQ} value was observed, which had a low Brinnel hardness value. In the 16 % and 24 % side grooving cases the improvement on the toughness due to a softening of the material seems to be compensated by the increasing constraint introduced by a greater side groove ratio.

In relation to the other materials, the results of the J_{IQ} values were consistent.

Conclusions

The S_{pb} method behavior was evaluated using two and three calibration points.

Originally, this method was proposed using three calibration points, which were the initial crack length, the final crack length, and a theoretical calibration point. There are some cases in which it is not possible to determine or measure a final crack length, for example in impact tests in which the specimen brakes in two halves. In such a case the evaluation of the S_{pb} method using only two calibration points, the initial crack length and the theoretical calibration point would be very useful. The S_{pb} method shows a very good performance when it was used with two calibration points. The differences on the crack lengths estimated with the ones measured on the fracture surface were less than 0.07 mm for the initial crack length and 0.5 mm for the final crack length. In every case, the differences were always less than the limit value.

J-R curves were determined for the three materials analyzed. An acceptable agreement was found between the S_{pb} method J-R curves and the ones determined using the crack length obtained by the compliance method used as reference.

The S_{pb} method will result in being helpful for cases in which high loading rates are applied. The authors consider that further work should be carried out in order to validate and generalize the precious results considering different test conditions and materials.

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