13th International Conference on Fracture
June 16–21, 2013, Beijing, China

Fracture Toughness of SE(B) Specimens of Steel in the Presence of Splitting

Pablo J. Lara Melcher, Enrique M. Castrodeza*

Laboratory of Fracture Mechanics, Department of Metallurgical and Materials Engineering, COPPE/Federal University of Rio de Janeiro, P.O. Box 68505, 21941-972, Rio de Janeiro, RJ, Brazil

*castrode@metalmat.ufrj.br

Abstract

Instabilities (pop-ins) in load-displacement records of fracture tests could be originated from small unstable crack growth in the main crack plane, as usual in welded joints, or from delamination of the ligament (splitting), as in some rolled steels. According to the standards, no matter the origin of the instability the fracture toughness need to be reported at the first significant pop-in. In most cases this treatment greatly penalizes the fracture toughness of the material. In that way a question arose: What would be the fracture toughness of a material featuring splitting if the specimen were not suffered split? To answer this question several test were made in rolled steels showing and not pop-ins from splitting. It is being now proposed that the change in the system energy associated to splitting instabilities could be neglected, the records corrected by adding the load drop caused by the split to the points on the right, and the toughness calculated at the maximum load. The results (for the magnitude of the instabilities we faced) showed that maximum load CTOD from corrected records and from records of the same material without pop-ins by splitting are statistically equivalent.

Keywords: Pop-in, Split-Out, Fracture Toughness, Rolled Steel.

1. Introduction

Pop-ins in load-displacement records of fracture tests are not always related to unstable crack growth and arrest in the main plane of the crack. Sometimes these instabilities are related to delamination (or splitting) of the ligament. This behavior could be present in some rolled steels and is related to some metallurgical characteristics of the material like crystallographic texture, elongated inclusions, banded microstructure, and/or central segregation, among others [1]-[3]. The origin of splitting is related to the stress triaxiality ahead of the crack-tip [2] [2] and the low toughness of the materials in the rolling plane, which can cause delaminations in the ligament in a plane perpendicular to the main crack one. An example of this behavior is shown in Figure 1.

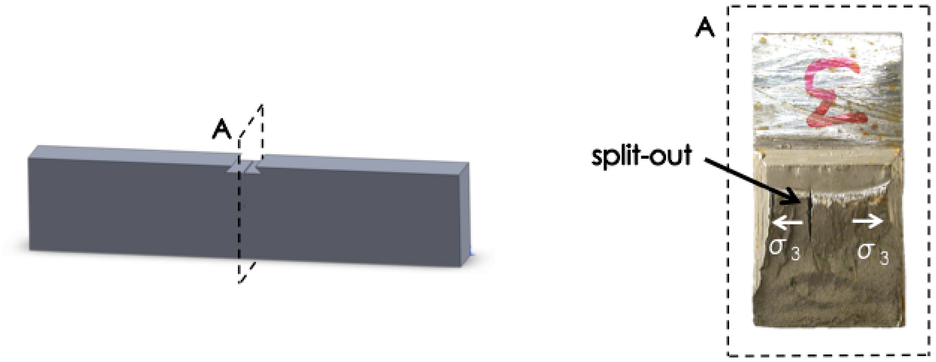

Figure 1. SE(B) specimen of rolled steel showing delamination (splitting) in the ligament.

When a split-out happens, one instability (pop-in) in the load-displacement records appears. Facing this kind of instabilities the standards have similar approaches, as shown in Table 1 [5]-[9].

Table 1. Excerpts of international standards on pop-ins caused by delaminations.

Standard	Excerpt
BS7448 part 1	Splits and delaminations can result in pop-ins with no arrested brittle crack extension in the plane of the fatigue precrack.
BS7448 part 2	Pop-in can be caused by an arrested crack running perpendicular to the plane of the fatigue precrack; this is sometimes referred to as a ‘split’. The fracture toughness at pop-in caused by a split needs to be reported. However, the assessment of the structural significance of the split is outside the scope of this standard.
ASTM E1290 ASTM E1820	If the pop-in is attributed to an arrested unstable brittle crack extension in the plane of the fatigue precrack, the result must be considered as a characteristic of the material tested.
DS EN ISO 15653	Pop-in can be caused by an arrested crack running perpendicular to the plane of the fatigue precrack. This is sometimes referred to as a “split”. The fracture toughness at pop-in caused by a split shall be reported, but might not characterize the fracture toughness of the material for the intended crack orientation. A different specimen and crack plane orientation might be necessary to characterize the fracture toughness of the material in the plane of the split. Assessment of the structural significance of a split is outside the scope of this International Standard.

As can be seen from Table 1, the standards do not offer alternative methodologies for fracture toughness evaluation when splitting occurs and the toughness basically needs to be calculated and reported at the first significant instability. The lack of alternatives for toughness evaluation in the presence of splitting could greatly penalize the toughness of the tested material, especially when the instabilities occur at the first stages of the test. Facing this scenario a question arose: What would be the fracture toughness of a material featuring splitting if the specimen were not suffered split? Or, in another words: It could be possible to estimate the fracture toughness of a material from a specimen that shows splitting? A possible answer to these questions was the main objective of the work and the results of our research follow.

2. Experimental

Fracture tests were performed on SE(B) specimens of rolled and accelerated cooled CLC DH36 ferritic steels (W=26 mm), as well as on conventional rolled API X65 and X70 steels (W=40 mm). The specimens were machined according to the ASTM 1820 standard in the LT orientation. The specimens were tested in an Instron 1332 servo-hydraulic testing machine with a 250 KN load cell, under displacement control and at different (low) temperatures. The specimens were submerged in an instrumented alcohol-cooled bath and the temperature was maintained at the nominal value with an accuracy of ±2°C. Load, crack mouth opening displacement and load line displacement were recorded. Additionally, on DH36 steels unloading compliance technique was applied for R-curves evaluation. J-Integral values and J-R curves were calculated according to the ASTM E1820 standard [8] and CTOD values were calculated according to the BS 7440 part 1 standard [5].

3. Results and Discussion

Figure 2a and 2b presents P-LLD and P-CMOD records of one test specimen of DH36 steel tested at –50°C. These records are representative of the behavior of specimens of the same steel at this temperature. As can be seen, the records show a pop-in caused by splitting. Figure 3 presents the J-R curve of this specimen. From Figure 2 it is possible to see that the pop-in occurred between the 5th and the 6th cycle in a total of 26 unloading-reloading cycles. The segment between the 5th and the 6th points in the J-R curve is pointed out by the arrow in Figure 3. It is interesting to observe that, without the help of the arrow, the position of the pop-in it is almost impossible to be identified in the J-R curve. In other words, there is no evidence of crack growth in the main plane of the crack associated to the split.

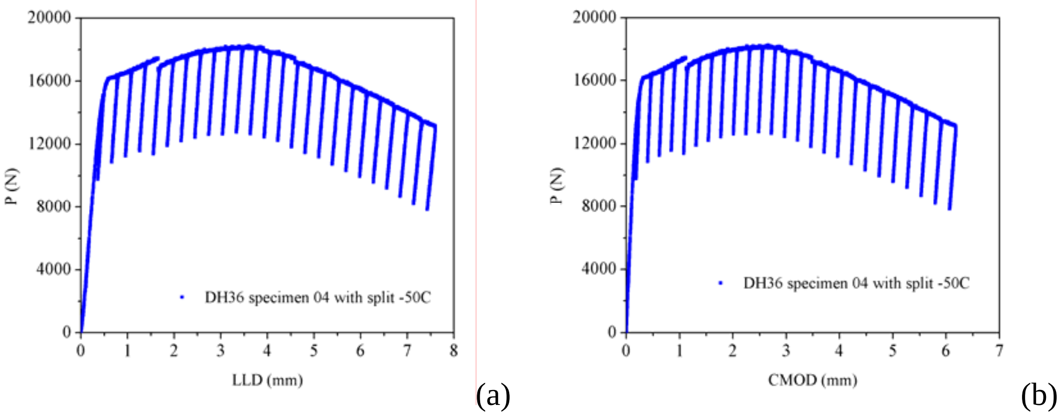

Figure 2. Experimental records of DH36 specimen 04 tested at -50°C. a) load vs. load line displacement; b) load vs. crack mouth opening displacement.

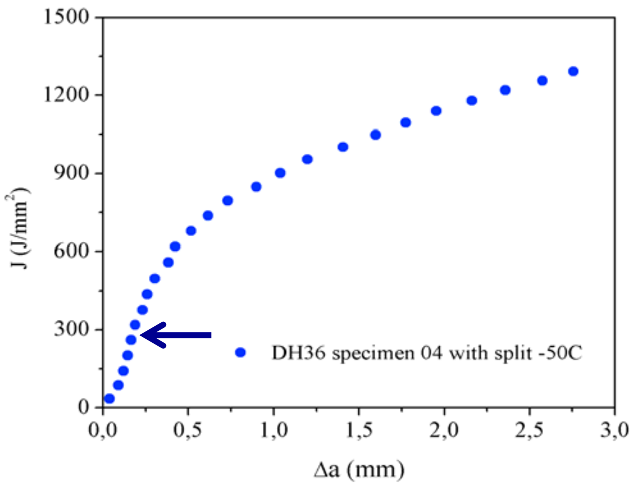

Figure 3. J-R curve of DH36 specimen 04 tested at -50°C.

This result shows that the change in the system energy associated to the pop-in caused by splitting could be almost completely related to the split formation itself and not to crack growth in the main plane of the crack. This idea is schematically shown in Figure 4, where the lower curve is represented in dots because its shape is still unknown. Being the energy change associated to splitting independent of the main crack growth the effect of the pop-in by splitting on the fracture toughness of the material could be neglected. But, how to neglect the effect of splitting in the records? We think that this could be done through corrections of the experimental records. Several corrections were analyzed, being adding the load drop during the instability to the points on the right part of the records (that is, after split-out) the straightforward one. After corrected, the record are ready to be analyzed through standard methodologies and the fracture toughness calculated at the maximum load point or at the main crack instability one.

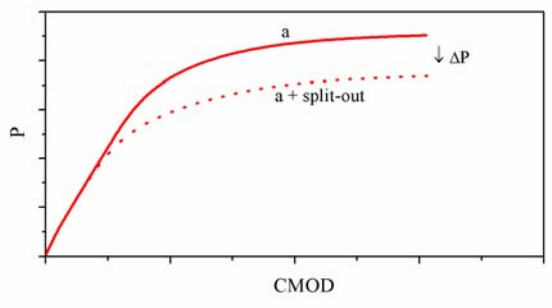

Figure 4. Scheme of the energy changes during a pop-in caused by splitting.

In a work on materials with delaminations Pisarski *et al.* [10] concluded that: "*when there is no significant loading perpendicular to the thickness direction, the pop-in can be ignored. Assuming that ductile behavior is indicated during the rest of the test, maximum load fracture toughness can be used to characterize toughness in the intended crack plane.*" We agree with this approach but we think that for improving the fracture toughness evaluation and for maintaining the equivalence among elastic-plastic methodologies, corrections of load-displacement records could still be necessary. The convenience of correcting load-displacement records was analyzed from a semi-hypothetical record, as follows.

Figure 5 presents modified P-LLD and P-CMOD records from the SE(B) specimens whose original records are shown in Figure 2. The unloading-reloading sequences are not shown here for clarity. The magnitude of the original load drop (approximately 4% of the load at the instability point) was now intentionally exaggerated by the addition of load drops of 10% and 20% as pop-ins. Additionally a corrected record was also added to the figure. When the fracture toughness at points A, B (as suggested by Pisarski), and C was calculated some controversial results were found. That is exemplified in Table 2, where J-Integral and CTOD values at points A, B and C are presented.

By comparing the results shown in Table 2 it is possible to see that $CTOD_A \approx CTOD_B \approx CTOD_C$ but $J_A < J_B < J_C$. Going further, when CTOD and J-Integral values are calculated at the beginning of each unloading-reloading sequence and the results plotted as J vs. CTOD (Figure 6), it is possible to see that J-Integral and CTOD values maintain linear proportionality before splitting in all records, as well as after splitting in the corrected record, but does not maintain the original proportionality after splitting in the uncorrected records. As can be shown, an increasing in the load drop in the pop-ins caused by splitting increases the deviation of J-CTOD pairs from its original equivalence. As far as we can understand, that effect is caused by taking into account in J-Integral calculations a change in the system energy that is not associated to crack growth in the pre-cracking plane and that did not substantially affected the main crack length nor the crack tip opening displacement. The load drop in such a kind of pop-ins is clearly associated to the creation of a crack in a plane perpendicular to the main crack one. The proposed correction to load-displacement records featuring instabilities by splitting resolves this issue, being J-Integral and CTOD values continuously equivalent. Obviously, small splits produced small load drops in the load-displacement records and the effect on the J-CTOD equivalence is much less perceptible, but always existent.

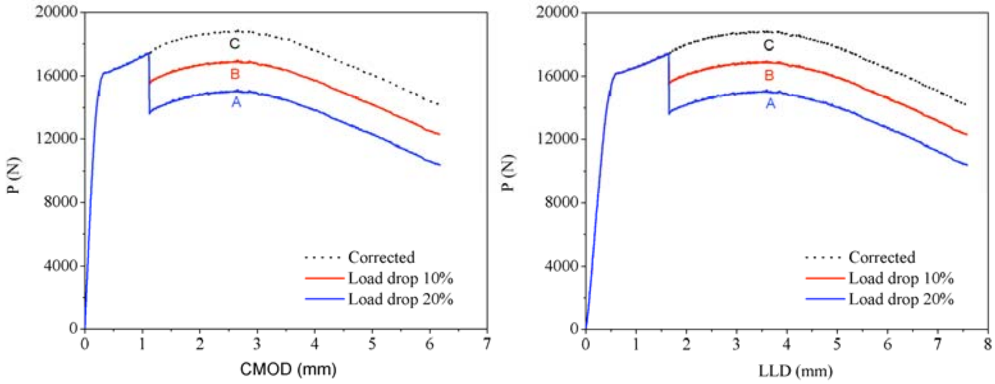

Figure 5. Semi-hypothetical P-CMOD and P-LLD records of a specimen of DH36 steel. The load drops at the instability were intentionally exaggerated.

Table 2. J-Integral and CTOD values calculated at points A, B, and C from the records shown in Figure 5.

Point	CTOD [mm]	J-Integral [J/mm^2]
A	0.623	513.33
B	0.624	546.27
C	0.628	590.63

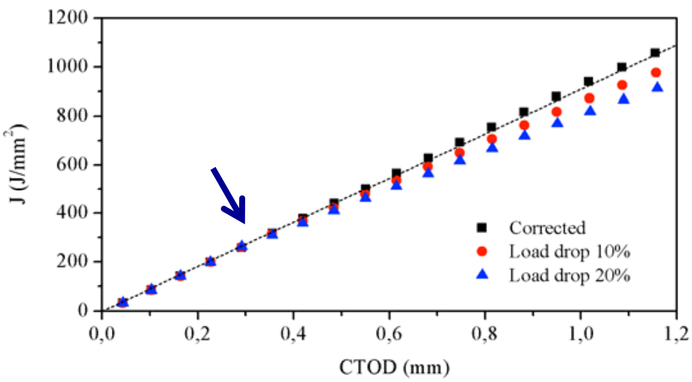

Figure 6. J-CTOD curves calculated from the records of Figure 5. The arrow indicates the position of splitting between the 5th and 6th unloading-reloading sequence.

The proposed correction of the load-displacement records has now been justified and the results of the whole experimental program will be now presented. When tested from room temperature to -30ºC the specimens of DH36 steel do not showed pop-ins. The specimens of this steel randomly showed pop-ins in the range from -40ºC to -58ºC. In all the cases the instabilities were associated to splitting. Almost 50% of the API X65 specimens showed splitting and mostly of API X70 specimens showed splitting at -20ºC. In most cases the splitting occurred before the attainment of maximum load plateau. Figures 7a, 7b and 7c show typical P-CMOD records with pop-ins of API X-65, API X-70 and DH36 steels, respectively (the unloading-reloading sequences of DH36 tests were removed from the records for clarity), as well as the corrected records. Figure 8 shows a comparison between the corrected records of Figure 7 and P-CMOD records of the same materials without split.

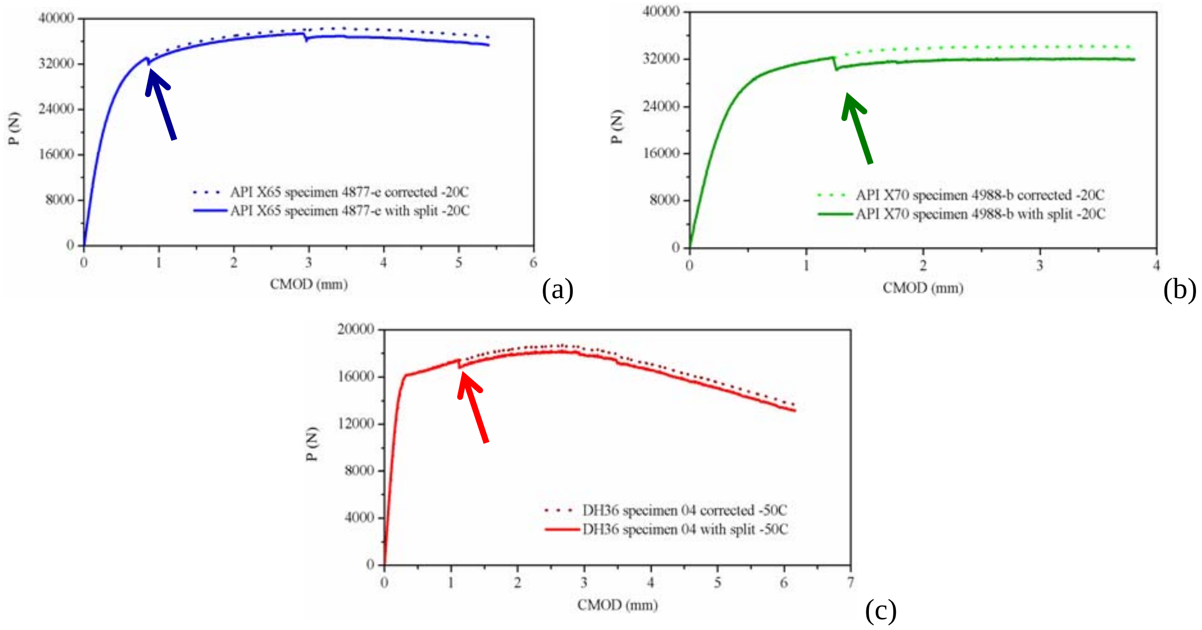

Figure 7. Original and corrected P-CMOD records of specimens featuring splitting. a) API X65, b) API X70, and c) DH36.

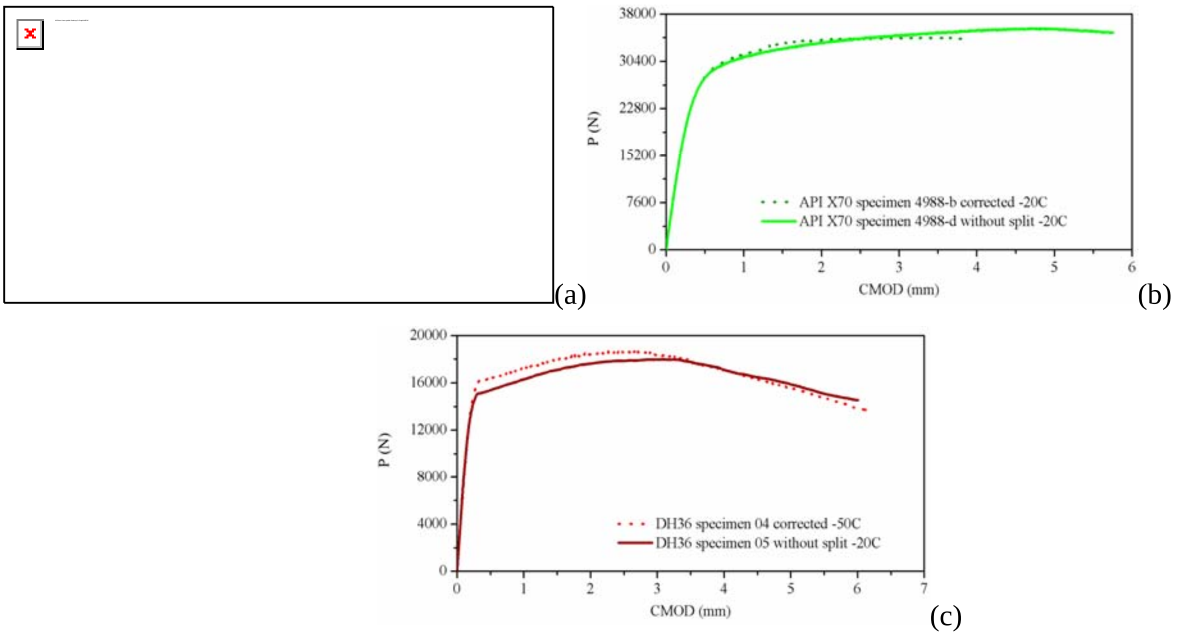

Figure 8. Corrected P-CMOD records and records from specimens of the same materials without splitting. a) API X65, b) API X70, and c) DH36.

Table 3 shows individual CTOD values of DH36 specimens calculated from the original and corrected P-CMOD records, as well as from specimens without splitting. Table 4 shows individual CTOD values of API X65 specimens, and Table 5 shows the same kind of data for API X70 specimens.

Table 3. Fracture toughness of SE(B) specimens of DH36 steel.

Specimen	Temp. (ºC)	Splitting	CTOD pop-in (mm)	CTOD max load (mm)	CTOD corrected (mm)
1	RT	No	--	0.663	--
3	-50	Yes	0.707	--	0.764
4	-50	Yes	0.284	--	0.723
5	-20	No	--	0.833	--
6	-20	No	--	0.688	--
7	-40	Yes	0.720	--	0.780
8	-40	No	--	0.707	--
9	-40	No	--	0.763	--
10	-50	No	--	0.775	--
11	-30	No	--	0.663	--
12	-30	No	--	0.800	--
13	-30	No	--	0.774	--
14	-30	No	--	0.692	--
15	-58	Yes	0.645	--	0.711
16	-55	Yes	0.588	--	0.675
17	-58	Yes	0.385	--	0.526
18	-55	Yes	0.248	--	0.591
19	-55	No	--	0.739	--
20	-55	Yes	0.670	--	0.737

Table 4. Fracture toughness of SE(B) specimens of API X65 steel.

Specimen	Temp. (ºC)	Splitting	CTOD pop-in (mm)	CTOD max load (mm)	CTOD corrected (mm)
4877-a	-20	No	--	0.882	--
4877-b	-20	No	--	0.796	--
4877-c	-20	No	--	0.918	--
4877-d	-20	Yes	0.698	--	0.962
4877-e	-20	Yes	0.166	--	0.815

Table 5. Fracture toughness of SE(B) specimens of API X70 steel.

Specimen	Temp. (ºC)	Splitting	CTOD pop-in (mm)	CTOD max load (mm)	CTOD corrected (mm)
4988-a	-20	Yes	0.714	--	0.863
4988-b	-20	Yes	0.254	--	0.744
4988-c	-20	Yes	1.089	--	1.201
4988-d	-20	No	--	1.104	--
4988-e	-20	Yes	0.793	--	0.963
6006T 01	-20	Yes	0.435	--	0.921
6006T 02	-20	Yes	0.256	--	0.592
6006T 03	-20	Yes	0.336	--	0.888
6006T 05	-20	Yes	0.262	--	0.791
6006T 07	-20	No	--	0.798	--
6006T 10	-20	Yes	0.791	--	0.910
6006T 11	-20	Yes	0.302	--	0.798

The mean and standard deviation of the different types of calculated CTOD are shown in Table 6, which also includes the minimum CTOD value of each set of specimens calculated according to the BS standard [5]. The mean values of DH36 steel were divided in two temperature ranges. One range going from room temperature to -30 ºC, in which no one of the specimens showed splitting, and another from -40 to -58 ºC.

Table 6. Minimum and mean CTOD values of the tested specimens.

Steel	Temp. (ºC)	Minimum CTOD (mm)	CTOD pop-in (mm)	CTOD max load (mm)	CTOD corrected (mm)
DH36	RT to -30	0.663	--	0.730 ±0.070	--
DH36	-40 to -58	0.248	0.531 ±0.194	0.746 ±0.030	0.688 ±0.088
API X65	-20	0.166	0.432 ±0.376	0.865 ±0.063	0.889 ±0.104
API X70	-20	0.254	0.523 ±0.299	0.951 ±0.216	0.867 ±0.159

A statistical analysis on the results of Table 6 using Student's t-tests [11] reveals, with 95% of confidence, that there is no statistical difference between CTOD values from corrected records and the CTOD values from specimens without splits. This result indicates that it could be possible to estimate the main crack fracture toughness of the analyzed steels from SE(B) specimen showing splitting, with reasonable accuracy. This was achieved through the proposed modification of the experimental records, based on the idea that the change in the system energy due to splitting is mainly associated to the creation of the split itself and can be neglected for the main crack toughness evaluation.

4. Conclusion

Based on the presented results and discussion it is possible to conclude:

Splitting in SE(B) specimens of DH36 steel did not influence the main crack length measured by the unloading compliance technique. As a result, the change in the system energy associated to the instability was totally related to the split creation itself.

The fracture toughness associated to the main crack of a specimen featuring splitting could be estimated, with reasonable accuracy, through the proposed correction of the original load-displacement records. The proposed correction consists in removing the load drop at instabilities associated to splitting.

J and CTOD values calculated from the modified records kept its equivalence along the entire test. When calculated from non-corrected load-displacement records of specimens featuring instabilities by splitting the J-CTOD equivalence deviates beyond the instability point.

The fracture toughness of SE(B) specimens of the same material showed no statistical differences when calculated from specimens featuring splitting and modified records or from specimens without splitting.

Acknowledgements

The authors gratefully acknowledge to PEMM/COPPE/Federal University of Rio de Janeiro by the financial support, to CAPES for the scholarship of Pablo Lara Melcher, and to the Eng. Wagner Duarte Flores and Usiminas for the DH36 steel samples.

References

[1] T. Tanaka, Controlled rolling of steel plate and strip. International Materials Reviews, Vol. 26, No. 1 (1981) 185-212.

[2] B.L. Bramfitt, A.R. Marder, A Study of the Delamination Behavior of a Very Low-Carbon Steel, Metallurgical Transactions A., Vol. 8A, (1977) 1263-1273.

[3] Y. Kimura, T. Inoue, F. Yin, K. Tsuzaki, Delamination Toughening of Ultrafine Grain Structure Steels Processed Through Tempforming at Elevated Temperatures, ISIJ International, Vol. 50, No. 1 (2010) 152-161.

[4] J. Perez Ipiña, I. Korin, Effects of divider orientation split-out on fracture toughness. Fatigue & Fracture of Engineering Materials & Structures, Vol. 36, issue 3 (2013) 242-253.

[5] BS 7448-1 (1991) (Incorporating Amendment No. 1 and Corrigendum No. 1) Fracture mechanics toughness tests - Part: 1 Method for the determination of KIc, critical CTOD and critical J values of metallic materials. 2002, BSI, 389 Chiswick High Road, London, United Kingdom.

[6] BS 7448-2 (1997) Fracture mechanics toughness tests - Part: 2 Method for the determination of KIc, critical CTOD and critical J values of welds in metallic materials. BSI, 389 Chiswick High Road, London, United Kingdom.

[7] ASTM E1290 (2008) Standard test method for crack-tip opening displacement (CTOD) fracture toughness measurement. ASTM International, West Conshohocken, PA 19428–2959, United States.

[8] ASTM E1820 (2011) Standard test method for measurement of fracture toughness. ASTM International, West Conshohocken, PA 19428–2959, United States.

[9] BS EN ISO 15653 (2010) Metallic materials. Method of test for the determination of quasistatic fracture toughness of welds. BSI, 389 Chiswick High Road, London, United Kingdom.

[10] H.G. Pisarski, R. Hammond, K. Watt, Significance of splits and pop-ins observed during fracture toughness testing of pipeline steel, Proceedings of IPC 2008, 7th International Pipeline Conference, Calgary, Alberta, Canada, 2008, ASME, Paper IPC 2008-64676.

[11] R. Liman Ott, M. T. Longnecker, An Introduction to Statistical Methods and Data Analysis, Brooks-Cole, Cengage Learning, Canada, 2010.