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Effects of divider orientation split-out on fracture toughness

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ABSTRACT The Split-out phenomenon is a sudden instability, which takes place near the crack tip, and is generated by a rapid growth and arrest of a crack at the divider orientation. This phenomenon is related to stress triaxiality in the front of the crack tip when the structure is under plane strain conditions, plus the existence of weak interfaces oriented normal to the thickness direction. The weak interfaces can be generated as a result of some metallurgical process such as hot-rolling lamination in materials with a high level of impurities, as well as steels where the structure results in a strong banding of ferrite and pearlite. When a cracked structure is loaded, the high σ_z stresses related to the plain strain state can lead to a split-out brought about by delamination of the weak interfaces. During a fracture toughness test, this is noticed as a drop in the load-displacement record, which is similar to that produced by the well-known pop-in instability in welded joints. Although the load drops are very similar in both phenomena, their etiologies are completely different, since the pop-in is produced by an unstable crack growth and its ulterior arrest, due to local brittle zones located generally at the heat affected zone (HAZ) at or near a welded joint. As the split-out has been less studied than the pop-in, and due to the similarities between both load-displacement records, it is very common to consider both instabilities under the same failure acceptance criteria. In this way, the split-out is usually treated as a critical event, and therefore, many materials are rejected when split-outs occur in fracture testings. However, when a split-out occurs, the σ_z stress is drastically reduced, leading to a condition close to a plane stress situation (in fact, the σ_z stress reduces to 0 at the crack surfaces of the split-out).

The aim of this work was to study the effect of the split-out in the fracture toughness of hot laminated steels working in the upper-shelf region. In order to achieve this, the fracture toughness was evaluated by means of the resistance curve J-R of the material, using a single specimen test method. The occurrence of load drop and displacement increase in the test record are explained based on a constant main plane crack length hypothesis.

Keywords fracture toughness; hot rolled steel; split-out.

NOMENCLATURE

α = Crack length
ASTM = American Society for Testing and Materials
CMOD = crack mouth opening displacement
HAZ = Head affected zone
J = fracture toughness parameter
J-R = Fracture toughness resistance curve
l_{SP} = split-out length
P = Load
SE(B) = Single edge notch bend specimen
T = Temperature
V = displacement measured at the load line

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W = SE(B) specimen thickness
Δa = Stable crack growth
ΔP_{SP} = load drop in the load-displacement record
ν = Poisson coefficient
σ_0 = Yield stress
σ_{UTS} = Ultimate stress
σ_X = strees in axis X
σ_Y = strees in axis Y
σ_{YS} = Yield stress
σ_Z = strees in axis Z
τ_{MAX} = Maximum Shear stress
τ_{YS} = Shear yield stress

INTRODUCTION

The split-out phenomenon is a sudden instability which takes place near the crack tip, and is generated by a rapid growth and arrest of a crack at the divider orientation, Fig. 1. This phenomenon is related to stress triaxiality in the front of the crack tip when the structure is under plane strain conditions, plus the existence of weak interfaces oriented normal to the thickness direction. Weak interfaces can be found in steels as a result of some metallurgical processes such as hot-rolling lamination in materials with high levels of impurities, as well as steels where the microstructure results in a strong banding of ferrite and pearlite.

When a cracked structure is loaded, the high σ_z stresses related to the plane strain state can lead to a split-out brought about by delamination of the weak interfaces. During a fracture toughness test, this is noticed as a sudden load drop in the load-displacement record, similar to that produced by the well-known pop-in instability in welded joints. Although the load drops are very alike in both phenomena, their etiologies are completely different, since the pop-in is produced by an unstable crack growth in local brittle zones generally at or near the heat affected zone (HAZ) in welded joints, and its ulterior arrest at more tough material.

As the split-out has been less studied than the pop-in from the viewpoint of fracture toughness tests, and due to the similarities between both load-displacement records, it is very common to consider both instabilities under the same failure acceptance criteria. In this way, the split-out is usually treated as a critical event, and therefore, materials are rejected when this event occurs in fracture testing without an evaluation of the real consequences that it can produce.

However, according to[1], weak interfaces at divider orientation can lead to an improvement of the fracture toughness by relaxing the stress triaxiality. When a split-out

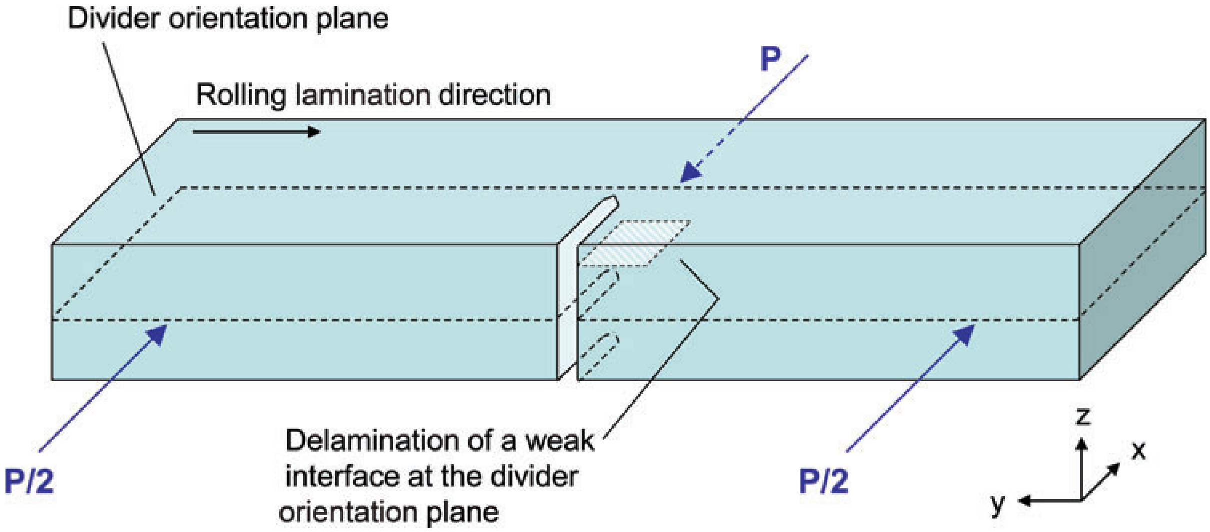

Fig. 1 Split-out plane at divider orientation.

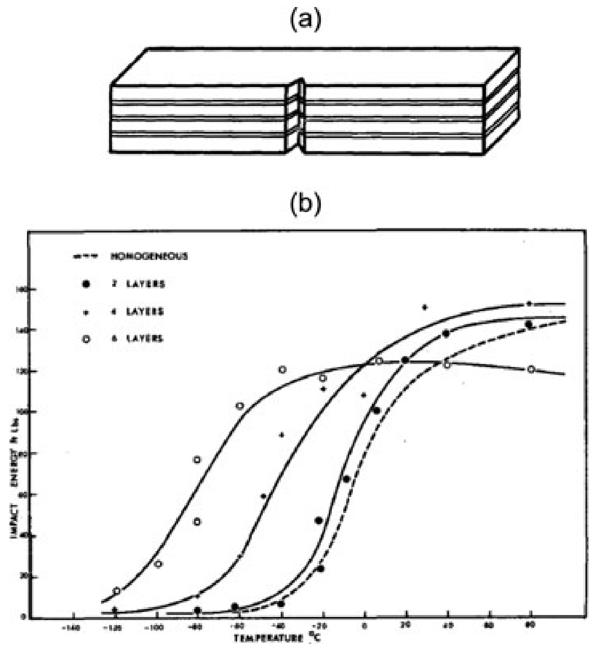

Fig. 2 Mild steel laminated specimen (a) and results (b) obtained by Embury *et al.*[2].

takes place, the σ_z stress is drastically reduced, leading to a condition closer to a plane stress situation (in fact, the σ_z stress component reduces to 0 at the crack surfaces of the split-out). Experimental evidence of such behaviour was obtained by Embury *et al.*[2] in earlier researches, in which notch-impact tests were performed on a model system of mild steel laminates containing a variety of interfaces (see Fig. 2). Results in their work were obtained by impact tests in terms of the ductile-to-brittle transition region, and showed a clear shift towards lower temperatures, as the number of interfaces increased. Fracture surfaces examination of specimens tested in this region showed that a pair of shear lips were formed on each subunit in contrast with the single pair of shear lips formed in the homogeneous specimen. Besides, a small reduction in the upper-shelf energy was also noted, although the authors attributed it to the replacement of a small cross-sectional area of mild steel by the weaker silver solder.

Table 1 Specimen details and testing parameters

Material	Sample	Specimen	W (mm)	σ_0 (MPa)	σ_{UTS} (MPa)	Test Temp (°C)
A	1	SE(B)	60	460.25	539.3	25
	2		60			25
	3		60			−20
	4		60			−20
B	5	SE(B)	40	530.8	576.6	25
	6		40			25
	7		40			−20
	8		40			−20

Shanmugam and Pathak[3] also obtained similar results, although in this case, they worked with a microalloyed steel which contained banding of alternate layers of ferrite and pearlite at the divider orientation. The results of Shanmugam and Pathak also showed a reduction in the upper-shelf energy as the contents of weak interfaces increased (i.e. the percentage of banding concentration in bands per millimetre).

The aim of this work was to study the effect of the split-out in the fracture toughness of two steels working at the upper-shelf region. In order to achieve this, the fracture toughness was evaluated by means of the resistance curve J-R of the material, using a single specimen test method. In this manner, the fracture toughness of the material can be evaluated before and after the occurrence of the split-out, in order to assess the effects of this phenomenon on the ductile crack growth resistance curve.

The discussion section is focused on several questions emerged from the obtained results. Such questions are

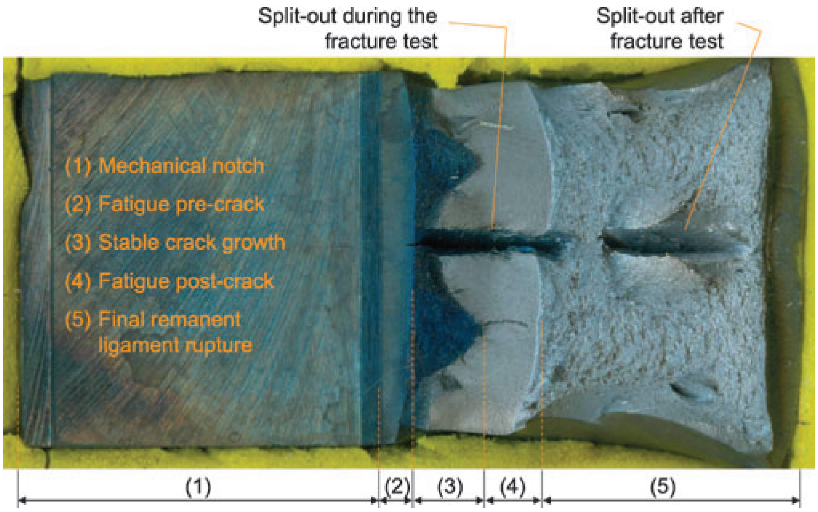

Fig. 3 Morphologies a crack surface can present.

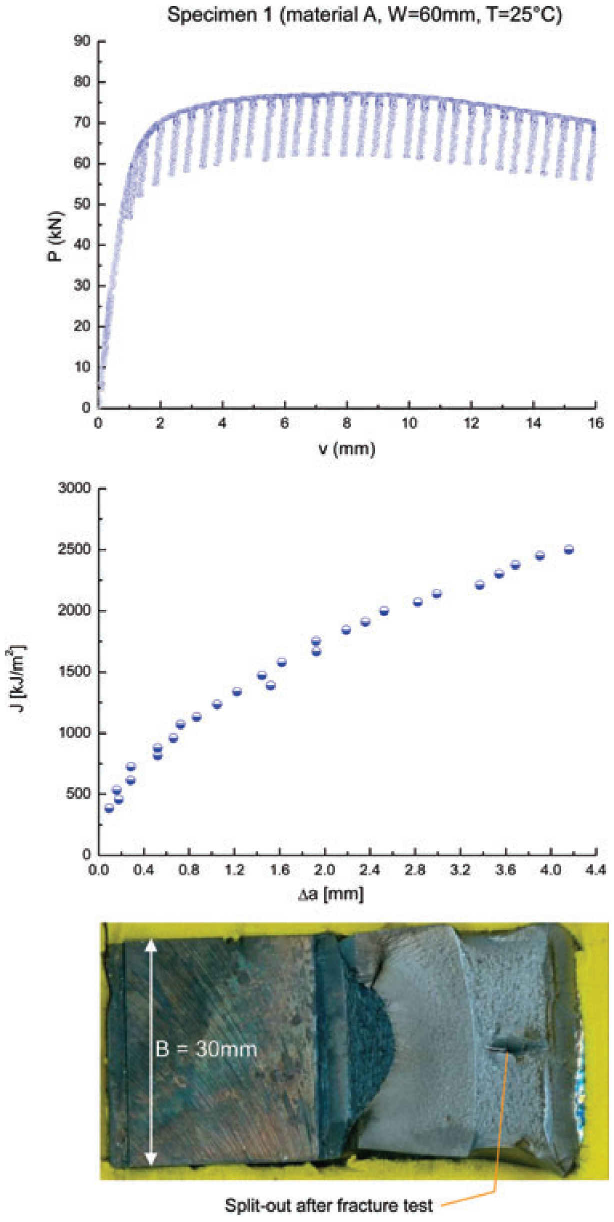

Fig. 4 Specimen 1 (material A, $W = 60$ mm, $T = 25°$C).

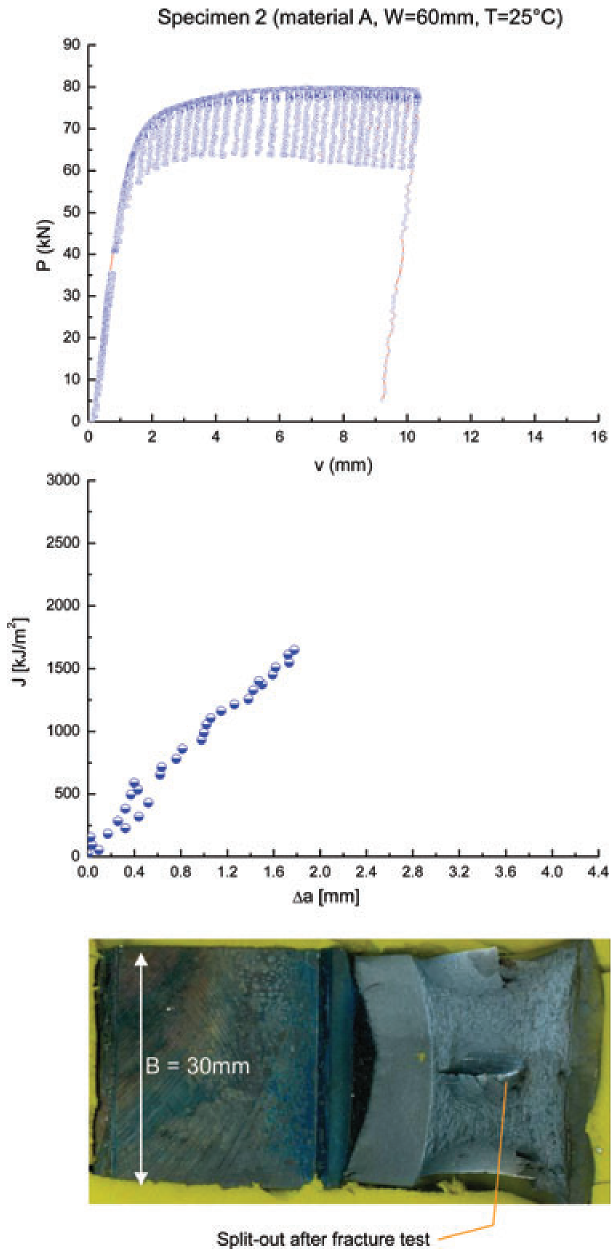

Fig. 5 Specimen 2 (material A, $W = 60$ mm, $T = 25°$C).

mainly related to the temperature dependence of the phenomenon, the load drop and displacement increment in the load-displacement record and the reduction observed in the fracture toughness after the split-out occurrence.

EXPERIMENTAL PROCEDURE

Two high toughness pipe steels, with tensile properties similar to those of API-5L X65 (see Table 1), were tested at low (–20°C) and room (25°C) temperatures.

Test were performed on SE(B) specimens with dimensions given in Table 1, using a displacement control system. J-R resistance curves were obtained following ASTM E1820 (2008)[4] and using the unloading compliance technique to measure the stable crack growth.

After the tests, the specimens were broken in two pieces by using post-fatigue cycles, in order to reveal their fracture surfaces (in some cases, before the post-fatigue cycles, the specimens were also coloured by means of a heat-tinting treatment to obtain a better contrast in the surface morphology and to differentiate split-outs occurred during the tests from those that were created at the moment of final fracture). Then, crack lengths and the

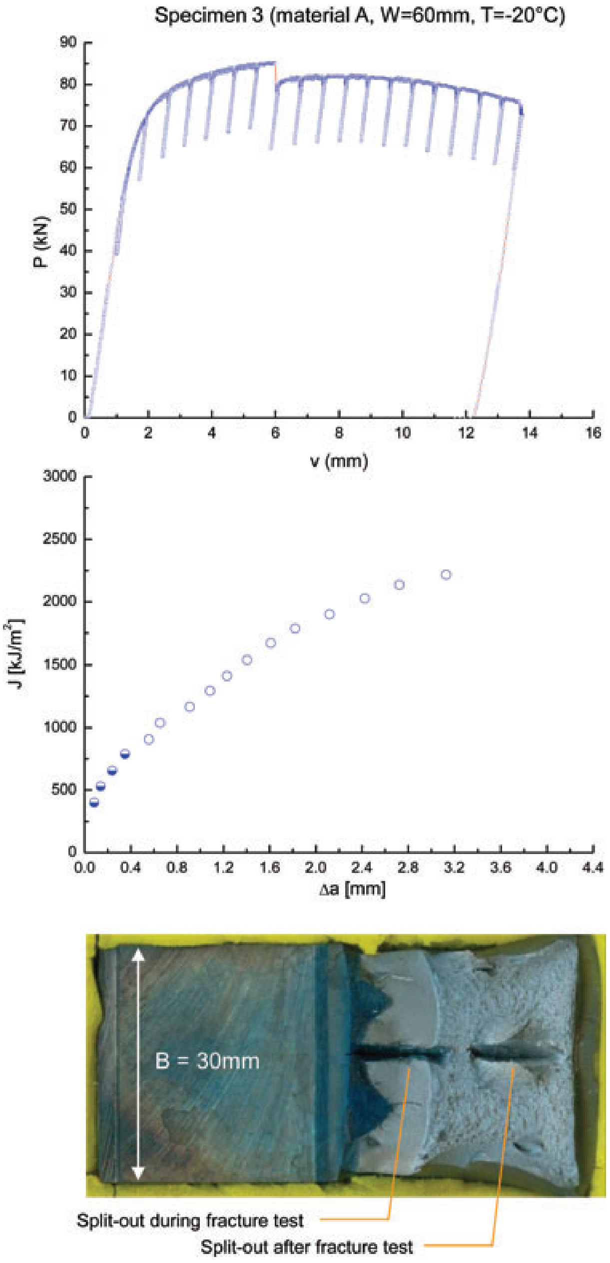

Fig. 6 Specimen 3 (material A, $W = 60$ mm, $T = -20°$C).

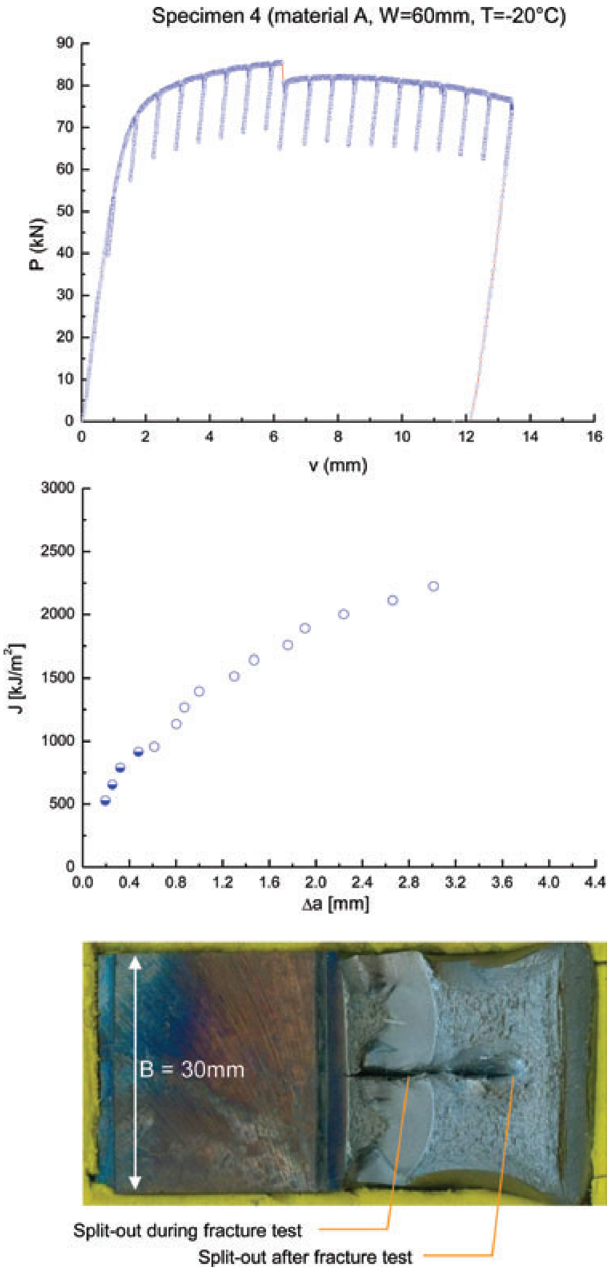

Fig. 7 Specimen 4 (material A, $W = 60$ mm, $T = -20°$C).

split-out lengths were measured from high-resolution images taken by an optical scanner[5]. With the aim to clarify this issue, Fig. 3 shows a detailed explanation of the morphologies a crack surface can present. Note that some split-outs took place after the fracture toughness test, during the rupture of the final remaining ligament, which was carried out at low temperature in order to minimize plastic deformation by using a hand-hydraulic press. As this process corresponds to the preparation of the sample after the test, these split-outs were disregarded and therefore excluded from further discussions.

RESULTS

Results related to material A ($W = 60$ mm) are shown in Figs 4–7, whereas those results corresponding to material B ($W = 40$ mm) are shown in Figs 8–11. Each figure shows the load-displacement record ($P - v$, where P is the load and v is the displacement measured at the load line), the J-R curve ($\mathcal{J} - \Delta a$, where $\mathcal{J}$ is the fracture toughness parameter and Δa is the stable crack growth), and the crack surface of the specimen tested. As it can be seen, only the tests carried out at low temperatures showed split-outs

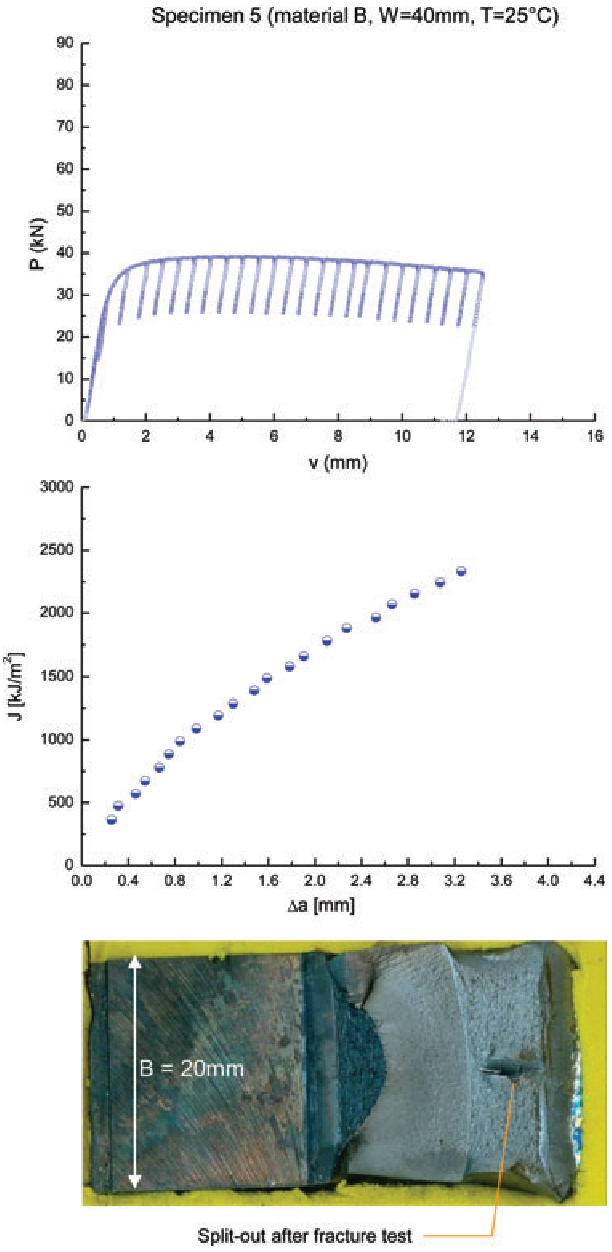

Fig. 8 Specimen 5 (material B, $W = 40$ mm, $T = 25°$C).

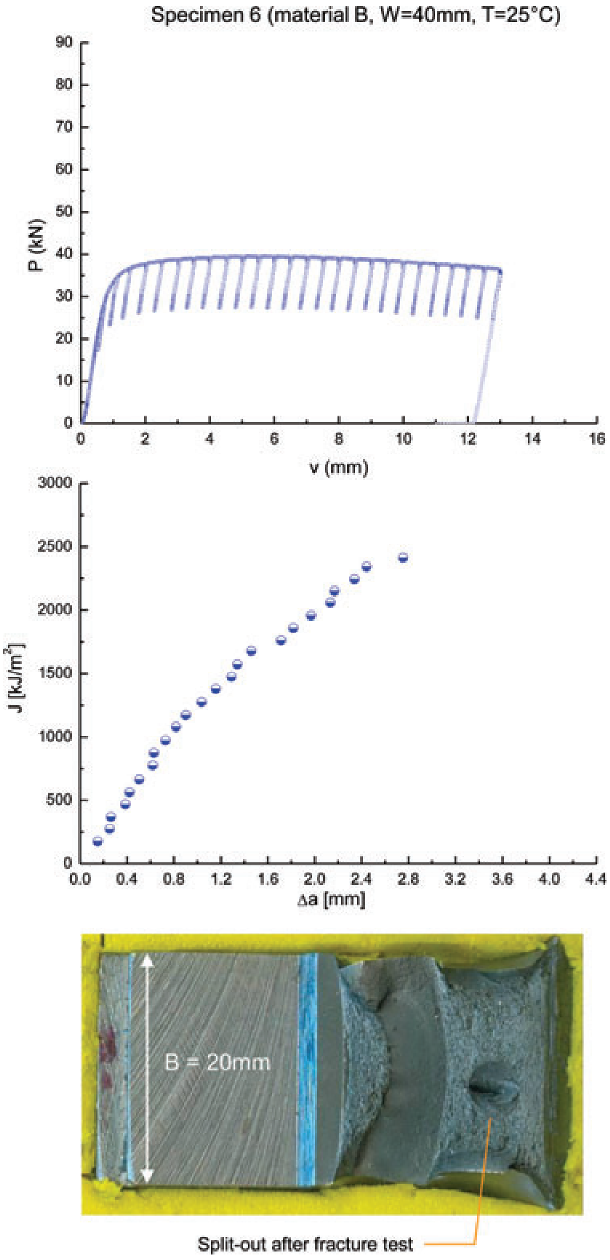

Fig. 9 Specimen 6 (material B, $W = 40$ mm, $T = 25°$C).

during the fracture test, which were clearly noted by the sudden load drop in the load-displacement record, and also in the J-R curve (note that half-full circles correspond to the data before the split-out, whereas empty circles correspond to the data after the split-out). Table 2 also summarizes two characteristics about the observed split-outs: the split-out length (l_{SP}) and the load drop (ΔP_{SP}) in the load-displacement record.

Referred to the fracture surfaces (see Figs 4–11), a clear difference in the stable crack growth path is noticed in those specimens where split-outs took place, denoted by a smaller crack growth at the new free surfaces created where the split occurred. Therefore, the fissures showed a particular appearance, with the development of two crests at both sides of the split-out.

Finally, the results depicted in Table 2 indicate that the split-out lengths took about 20% of W ($l_{SP} / W \approx 0.2$) in all the cases. On the other hand, the load drop observed in each material were somewhat different; being about 5.5% in material A and 8.4% in material B.

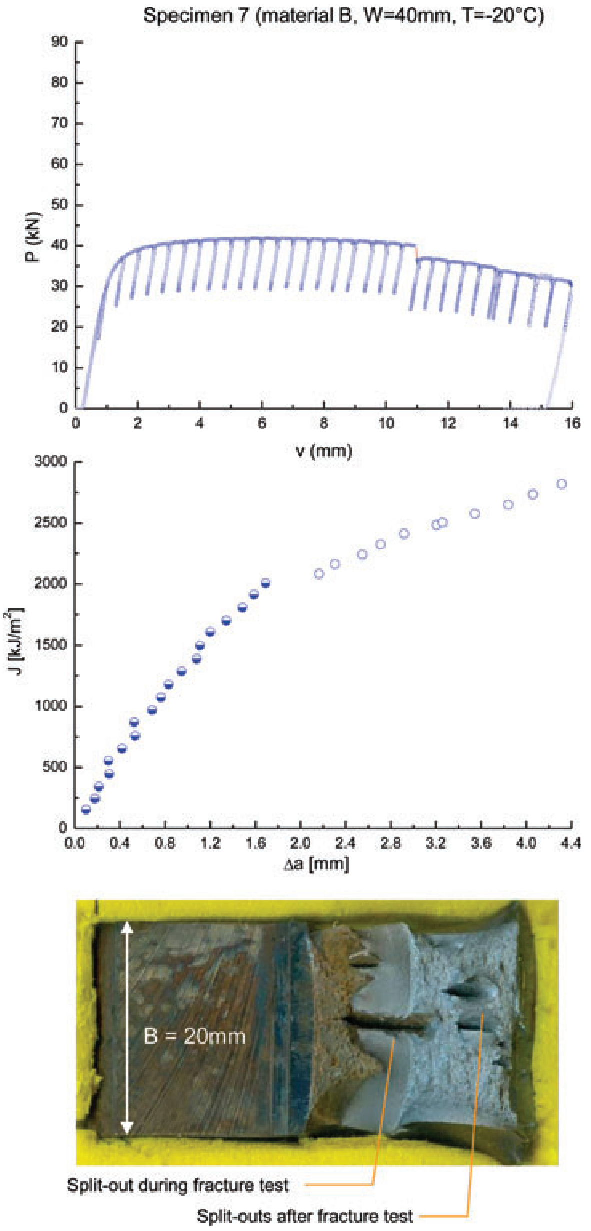

Fig. 10 Specimen 7 (material B, $W = 40$ mm, $T = -20°$C).

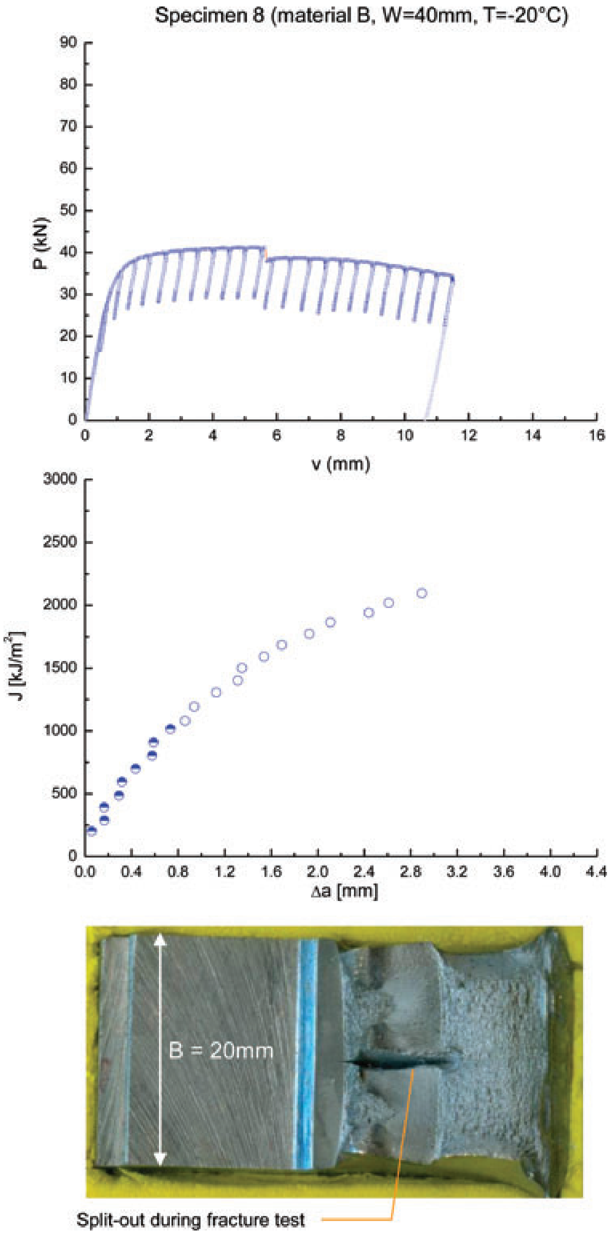

Fig. 11 Specimen 8 (material B, $W = 40$ mm, $T = -20°$C).

DISCUSSION

At the end of the Introduction section, some questions emerged from the obtained results were presented. The corresponding explanations follow.

Why did the split-outs occur only at low temperatures in the performed tests?

A simple mental model that could be useful to understand the split-out phenomenon is to consider the specimen as two specimens loaded in perpendicular directions, as depicted in Fig. 12. While the actual specimen is loaded by the testing machine, the imaginary specimen (which have the plane of the crack aligned with the plane of the split-out) is subjected to the σ_Z stress related to the constraint generated due to the stress triaxiality. In this way, the temperature dependence of the split-outs observed in the tests, could be explained by the increment in yield stress, σ_{ys}, with the decrement in temperature that could make the weaker interface to crack by means of the split-out, entering in the ductile-to-brittle transition region. Meanwhile, in the principal crack plane the increment in σ_{ys} is not enough to trigger the main crack. As a result,

Table 2 Split-out length (l_{SP}) and load drop (ΔP_{SP})

Sample	W (mm)	lSP (mm)	lSP/W	ΔP (kN)	$\Delta P/P$ (%)	Test Temp (°C)
1	60	–	–	–	–	25
2	60	–	–	–	–	25
3	60	12.479	0.21	4.804	5.65	−20
4	60	11.685	0.19	4.51	5.27	−20
5	40	–	–	–	–	25
6	40	–	–	–	–	25
7	40	8.528	0.21	3.503	8.75	−20
8	40	9.521	0.24	3.303	8.02	−20

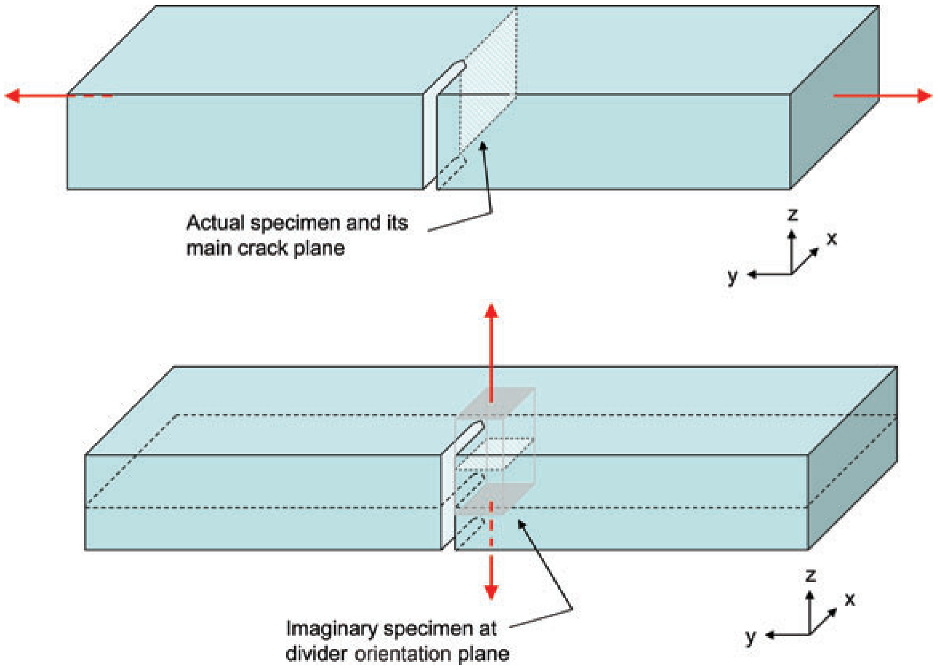

Fig. 12 Model considering specimen as two specimens loaded in perpendicular directions.

this behaviour can be interpreted as the material showing an anisotropy not only in the yield stress, but also in the ductile-to-brittle transition.

Why does the load fall in the load-displacement record when the split-out takes place?

A stress re-distribution takes place as a consequence of the split-out occurrence. Fig. 13(a) shows a diagram of σ_Y stress distributions in the X axis before and after the split. This analysis supposes valid the Westergaard–Irwin equations in the elastic region ahead the crack tip and a perfectly plastic material ($n = 1$) in the plastic region. Under these assumptions, the stresses before the split-out of a point A in the crack plane ($\theta = 0$) and forward the crack tip corresponding to plane strain conditions are $\sigma_X = \sigma_Y = 3\sigma_{\mathrm{YS}}$ and $\sigma_Z = \nu(\sigma_X+\sigma_Y) \approx 2\ \sigma_{\mathrm{YS}}$. After the split-out, σ_Z drops to zero in the free surfaces and therefore σ_X and σ_Y decrease up to σ_{YS} because of $\tau_{\max}$ can not be larger than τ_{YS}. A similar qualitative result is achieved for the case where the point of analysis is inside the elastic region (point B). It must be noted the increment in the plastic zone size from that before the split-out (red hatched circle) to that left after the occurrence of the split-out (blue hatched circle).

As well, Fig. 13b shows the schematically the σ_X, σ_Y and σ_Z stress distribution in the Z-axis, where it is notorious the decrement of tension in the zone where the split take place ($Z = 0$). In the case of tensile load over a specimen, the applied load is the integral in the area of the stress acting in the remaining ligament. In bending things are a little bit more complex, although the area below the curve in a line through the thickness passing by the plastic zone, Fig. 13b, can be related to the applied load. As this

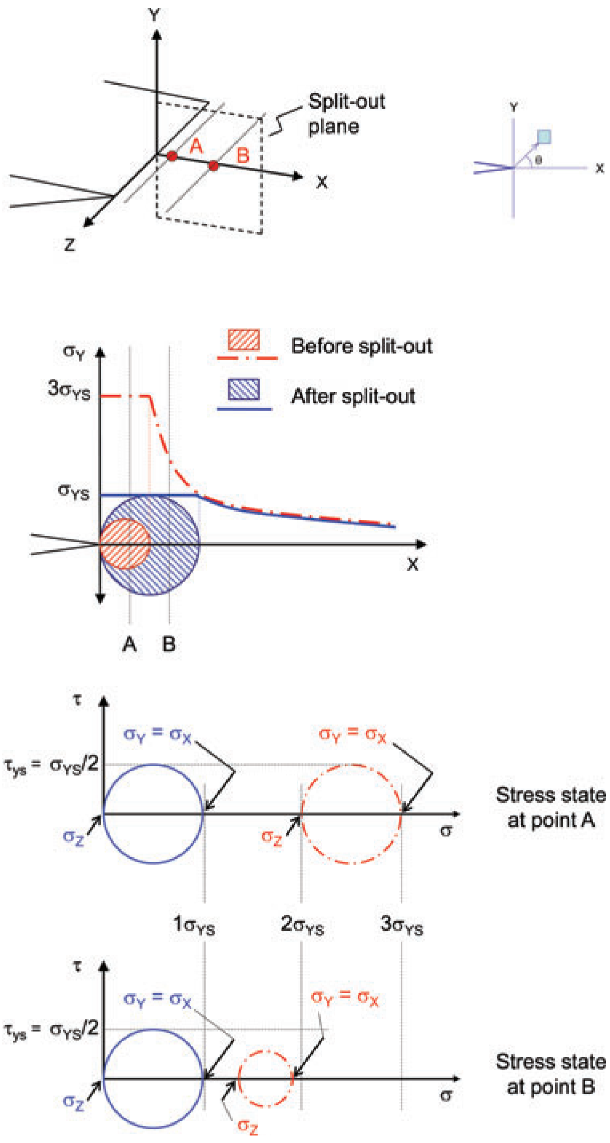

Fig. 13 σ_Y Stress distribution at X axis before and after split-out (a), and σ_Y, σ_X and σ_Z stress distribution at Z axis before and after split out.

figure shows, this area is lower after the split-out than before it and therefore the load must decrease. Similar results can be obtained with more complex models. This effect may also be understood from the analysis of the kinematic chain of the load machine, as it is explained in the following point.

Does the load drop and displacement increment due to the split-out occurrence implies a crack growth?

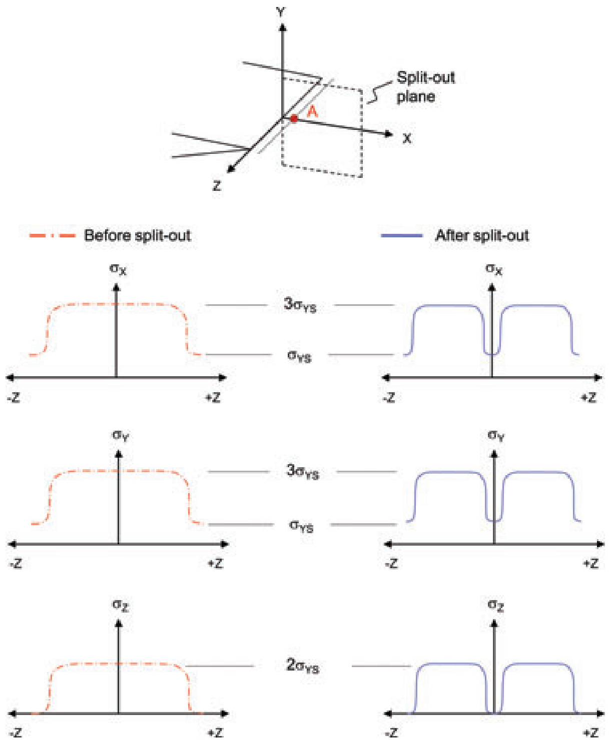

Fig. 13 Continued

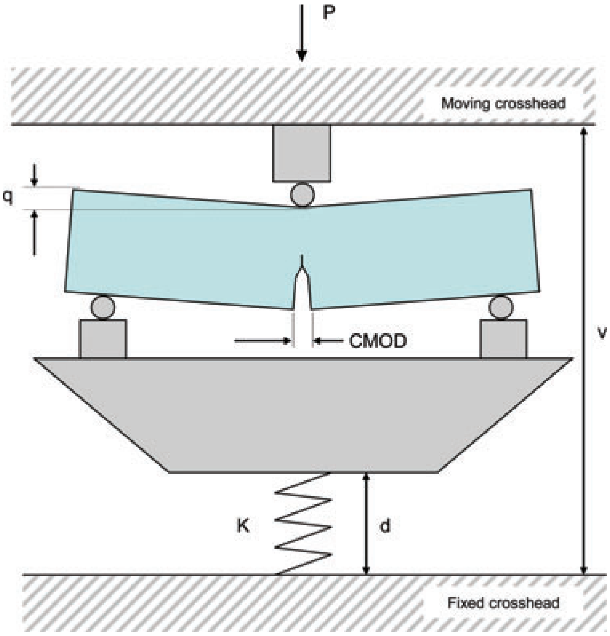

Fig. 14 Displacement components related to the three point bend specimen test.

As it happens in pop-ins, a decrease in load and an increment in displacement occur after the split-out. In the first case this is due to an unstable crack growth followed by crack arrest. In the case of split-out, there may be no significant length increment in the main crack plane because the increment in displacement could be as a consequence of the increment in plastic zone size at the new plane stress regions. Figure 14 can be useful to understand this.

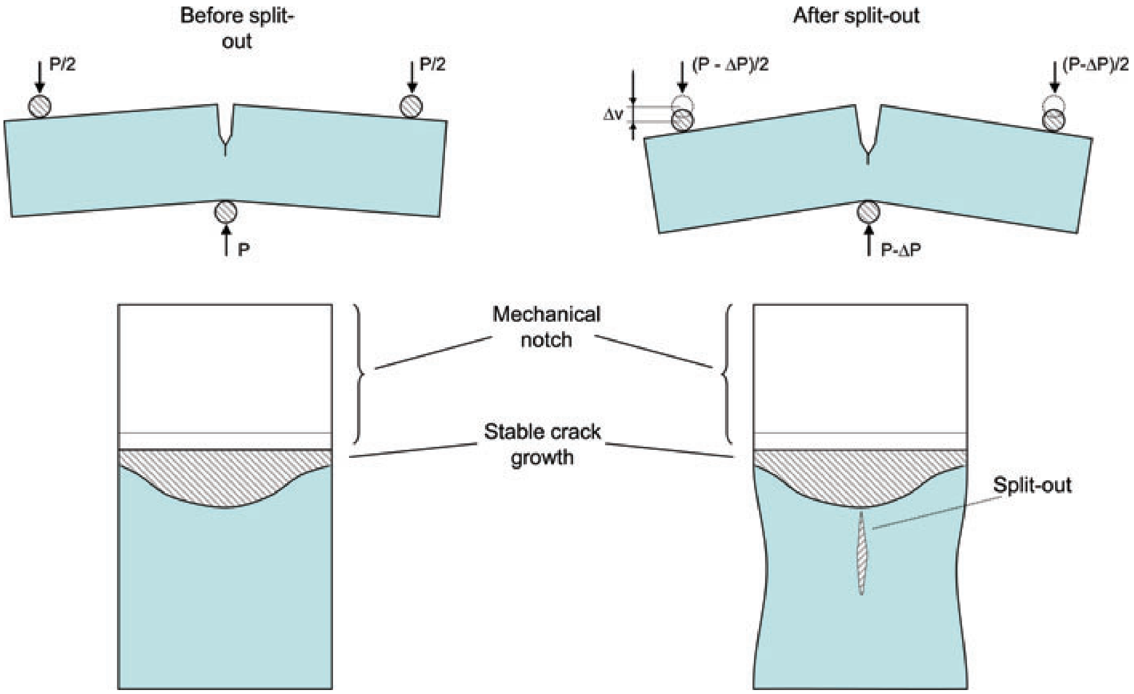

Fig. 15 Displacement effects due to the plastic deformation increment related to split-out occurrence.

This figure is an idealized representation of the important displacement components, which arise when a three point bend specimen is tested.[6] The specimen is loaded by moving an actuator at a constant displacement rate. An actuator displacement v produces a force P and a specimen load point displacement q. Besides, a crack mouth opening displacement *CMOD* is generated. The force P also produces elastic deflections in other parts of the test fixture, in Fig. 14 all these displacements d are lumped together in an imaginary spring shown below the fixed bottom crosshead. If a pop-in occurs the specimen stiffness immediately reduces. This gives rise to the following changes:

(1) *CMOD* and q increase;
(2) P reduces;
(3) d increases;
(4) v is assumed constant (displacement controlled machine).

On the other hand, when a split-out occurs, the same changes as listed above take place, but in this case these could not be necessarily related to a stiffness reduction. It would be possible that the increase of q and the decrease of P were caused by the increase in plastic deformation brought about when the split-out occurred, see Figs 13 and 15.

The main consequence of such assumption is that no crack growth (in the main plane) is associated with the split-out phenomenon. Fig. 16 summarizes the explained before for each kind of instability in terms of the sample stiffness.

Although these assumptions are sustained by the significant plastic strain observed around the split-out zones, they are not easy to verify because no unloading–reloading is possible to perform just before the split out. A continuous crack length monitoring method would be better than unloading compliance.[7,8] Potential drop and double clip gauge methods are going to be applied in order to verify the validity of this assumption in a future work.

What happens with the material toughness after the split-out?

In order to assess the effect of the split-out, J-R curves of specimens in which the phenomenon occurred were compared against others where split-outs did not take place. Although the J-R curves with and without split-out correspond to different testing temperatures, a very similar behaviour was expected, since the material behaviour corresponded to the upper shelf at both temperatures and the difference in yield stress is low.

Figure 17 shows a relevant example of the behaviour observed in all the cases: before the split-out, a very good matching between the J-R curves is observed. However, a notorious decrement in the slope of the J-R curve was observed after the split-out. This behaviour corresponds to a reduction in the tearing modulus $T = f(dJ/da)$, which indicates a lower capacity of the material to avoid ductile instability.

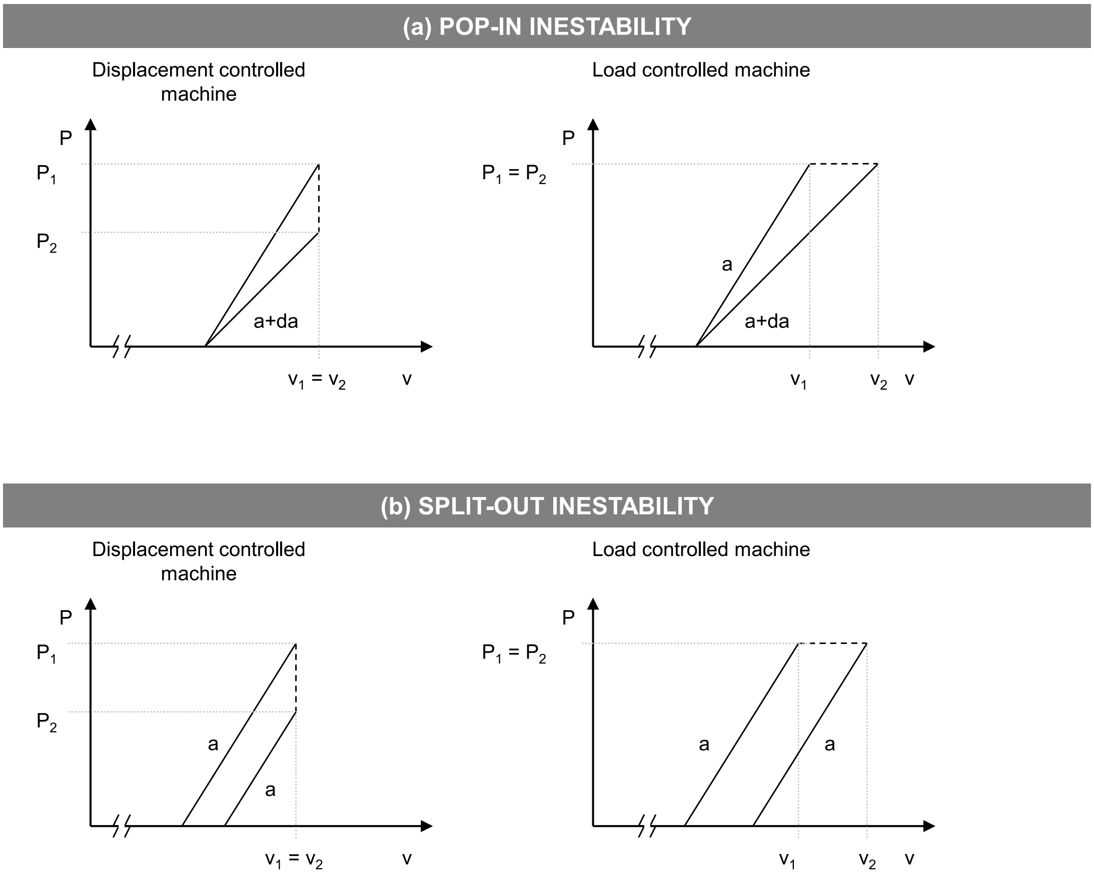

Fig. 16 Pop-in instability (a) and split-out (b) in terms of stiffness analysis of the system.

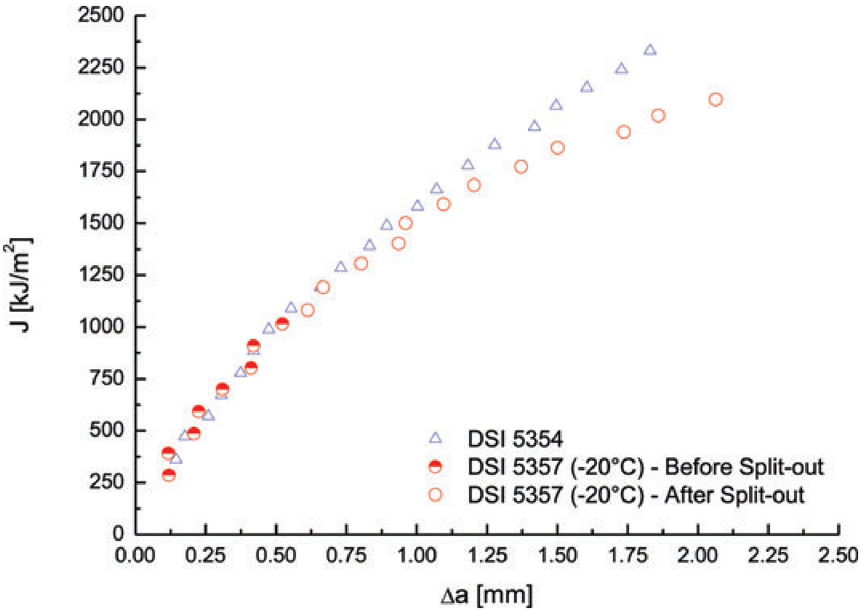

Fig. 17 Resistance curve of specimens with and without split-out delamination.

This interesting result is totally opposed to that postulated before the work; and also to that analysed in bibliography[1–3] which indicates that the split-out generates a more 'plain stress state', thus the material toughness should increase after the split.

A suitable explanation of this behaviour have not been achieved yet. An experimental program, which contemplates these unclosed matters is under development.

CONCLUSIONS

In this work aspects of fracture toughness related to the split-out phenomenon were evaluated. The fracture tests were carried out in two steels at different temperatures and the crack growth was measured by means of the unloading compliance technique. The following mainly conclusion can be highlighted:

1. The split-out phenomenon was observed only at low temperature in the samples tested, which implies that the material could present an anisotropy in the ductile-to-brittle transition.
2. The load drop and displacement increment that occurred by the split can be explained under the assumption of no crack growth in the main crack plane.
3. No increment in the fracture toughness was observed in the tests. On the contrary, a decrement in the fracture toughness denoted by a reduction in the tearing modulus $T = f(dJ/da)$ was observed.

Acknowledgements

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