



XXIV Italian Group of Fracture Conference, 1-3 March 2017, Urbino, Italy

Validation of a low blow specimen technique for R-curve determination using a drop tower

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Abstract

Fracture mechanics based component design requires appropriate fracture mechanics toughness data with respect to both, loading rate as well as test temperature. Taking high-rate loading into account such as with accidental scenarios, different standards such as ASTM E 1820 or BS 7448-3 provide some information on dynamic fracture mechanics testing. Nevertheless, the designations differ so that a validation of the own material specific test method used for dynamic R-curve determination is mandatory. In order to address this for ductile cast iron materials an experimental method for the reliable determination of dynamic J-integral crack resistance curves at $-40\text{ }^{\circ}\text{C}$ following the multiple specimen approach has been established and validated. The experimental concept offers some additional valuable features. Single values of dynamic crack initiation toughness can be determined using a single specimen technique based on crack sensors. Furthermore, an experimentally independent method is provided according to which CTOD δ_5 R-curves can be established. The focus of the present paper is on the validation of the experimental low blow technique using a drop tower test system.

A drop tower test system was developed and set up to perform low blow tests at temperatures down to $-40\text{ }^{\circ}\text{C}$. The system allows for a variation of the impact mass and height and was optimized for testing of ductile cast iron at stress intensity rates from approximately $5 \cdot 10^4$ to $3 \cdot 10^5$ $\text{MPa}\sqrt{\text{ms}}^{-1}$. This range of loading rate is characteristic for instance with crash scenarios of heavy sectioned DCI casks for radioactive materials. In order to address characteristic challenges of impact tests (test duration of microseconds up to milliseconds, inertial effects, signal oscillations), an appropriate full bridge strain gage method for the measurement of force directly on the specimen as well as a non-contact measurement of load line displacement using an optical extensometer have been developed and validated.

The low blow test requires either to prevent bouncing strikes of the hammer by using the stop block technique or to catch the hammer after its first strike. Both options are not part of the experimental concept and setup which have been realized here. The paper describes investigations which have been performed in order to make sure that bouncing strikes of the hammer do not cause additional crack extension in the specimen. This is necessary to ensure a unique relation between the work done and the

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achieved crack extension. The investigations covered the analysis of limit loads of the specimen with respect to the measured force. The measured stiffness of the specimen was assessed and signals of crack sensors were analyzed. Furthermore, an analysis of the mechanical behavior of the loading system and the specimen by optical observation was performed. Corresponding results are discussed in the paper. It had finally been proven that additional crack extension in the specimen due to bouncing strikes of the hammer is not to be expected under the given conditions of test setup, material and loading. It can be seen as a major experimental advantage that the striker does not have to be caught after the low blow test.

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Peer-review under responsibility of the Scientific Committee of IGF Ex-Co.

Keywords: Dynamic fracture mechanics; R curve; low blow; drop tower; ductile cast iron

1. Introduction

Fracture mechanics based component design requires appropriate fracture mechanics toughness data with respect to both, loading rate as well as test temperature. Taking high-rate loading into account such as with accidental scenarios, different standards such as ASTM E 1820 (2013) or BS 7448-3 (2005) provide some information on dynamic fracture mechanics testing. Nevertheless, the designations differ and BS 7448-3 does not address the determination of R-curves at all. The new ISO 26843 (2015) standard issued in 2015 is dedicated to fracture toughness tests at impact loading rates but exclusively limited to 10 mm thick pre-cracked Charpy type test pieces. Therefore, it is at the discretion of the test laboratory to make sure that the own material specific test method used for dynamic R-curve determination is designed, performed and validated properly. Within this procedure, transferability of measuring techniques from one lab to another, from small to large scale tests or vice versa and of more or less common advice from standards to the own very special experimental task cannot simply be taken for granted. In contrary, it is of vital importance to validate the basic measured quantities independently before using the data for further analyses and to establish material characteristics.

The results presented in this paper are part of investigations which were performed at BAM to establish and validate an experimental setup and an analysis procedure for the determination of dynamic R curves on ductile cast iron materials at $-40\text{ }^{\circ}\text{C}$ using a drop tower test system and the multiple specimen approach. Basic aspects of the experimental setup have already been reported in Baer (2012). This reference covers the development and validation of a strain gage based force measurement method on the specimen. Solutions for non-contact displacement measurement and numerical determination of the displacement by double integration of the force-time record have been discussed as well. The focus of the present paper is on the validation of the low blow multiple specimen technique using the BAM drop tower test system.

2. The BAM drop tower test facility

The BAM drop tower test facility, Fig. 1, was designed and optimized to perform fracture mechanics low blow tests on bend type specimens of ductile cast iron materials (DCI). Single edge bend specimens SE(B)25 (length 138 mm, width 25 mm, thickness 25 mm, $a_0/W = 0.5$) are the preferred specimen size. Nevertheless, the test setup allows for variable adaptation to other specimen sizes. The mass of the hammer and its height of fall may be varied (max. 20 kg, max. 3 m, max. initial speed of the hammer approximately 7.7 ms^{-1}). Stress intensity rates in the linear-elastic range of approximately $1\cdot 10^5$ to $2\cdot 10^5\text{ MPa}\sqrt{\text{ms}^{-1}}$ are typical with DCI low blow tests. The loading fixture complies with ISO 12135 (2002) and is designed to minimize friction by allowing the rollers to move outwards during loading. Fig. 2 exposes a detail of the hammer weight design which turned out to be essential for the analysis of the recorded test signals. Fig. 2(a) shows the hammer weight before and Fig. 2(b) after design optimization. The taller new design ensures that the susceptibility of the loading device to energy losses due to friction during the fall is maximally reduced. The beneficial effect of the optimized design is due to the mass of the hammer being positioned much closer to the gravity center axis of the hammer sledge than before thus preventing the risk of canting during the fall. If the energy losses are proven to be negligible, then the option exists to calculate the load line displacement by double integration of the force-time record instead of using expensive non-contact displacement measuring equipment. For details of the validation procedure see Baer (2012).



Fig. 1. BAM drop tower test facility (left: total view, middle: tempering chamber for cooling with liquid nitrogen, detail with specimen inside, right: triple point bending loading fixture with instrumented specimen and electro-optical camera for displacement measurement).

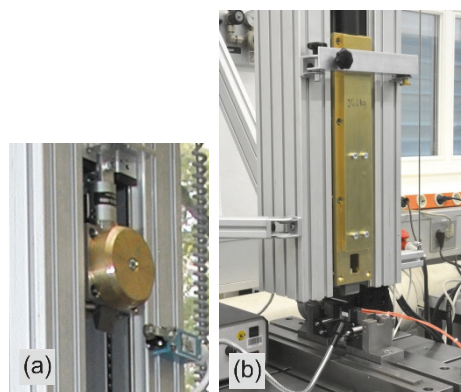


Fig. 2. Drop tower hammer weight, (a) before and (b) after design optimization.

2.1. Specimen loading behavior

The contact between the tip of the hammer and the specimen was monitored during the low blow test by video-optical analysis using a high-speed camera. Fig. 3 displays the force-time record of a typical low blow test on DCI together with images of the ligament where the hammer tip contacts the specimens upper side. A lift off of the hammer tip from the specimen was not detected for the initial stages of the test. The contact between specimen and hammer tip is rather maintained during the whole test. Point 6 in Fig. 3 marks the end of the loading phase in the low blow test. At this point the hammer starts moving upwards and the specimen starts elastic spring-back. Furthermore, the pictures reveal the successive formation of a small plastic zone ahead of the crack tip and opening of the fatigue precrack.

2.2. Analysis of specimen loading by the bouncing hammer

Basic principle of a low blow test is that a defined amount of energy is transferred to the specimen by a single hit of the hammer causing deformation and stable crack growth. For the fracture mechanics analysis, a unique relation is required between the work done at the specimen (area under the force-displacement record, J -integral) and the stable crack extension caused in the specimen. Nevertheless, in low blow tests the specimen experiences repeated,

successively damped load impulses after the initial hit of the hammer (the 'real' low blow test) due to bouncing strikes of the hammer, Fig. 4.

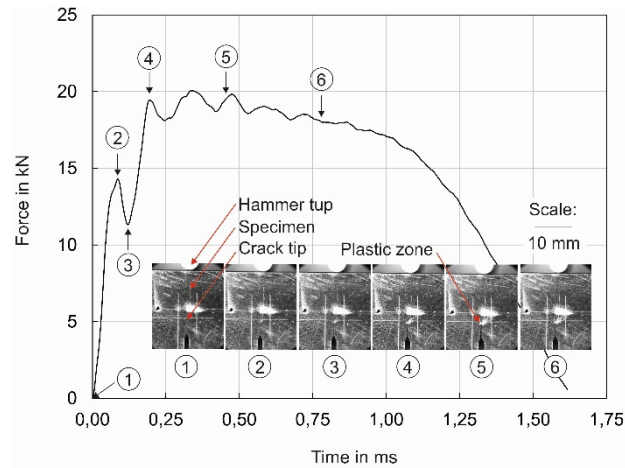


Fig. 3. Specimen loading behavior in a low blow test (initial speed of the hammer 1.67 ms^{-1} , stable crack extension 1.01 mm , camera recording speed 30.000 fps).

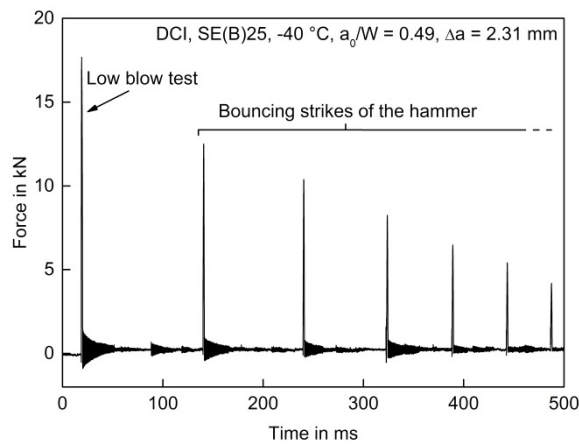


Fig. 4. Low blow test with successively damped load impulses after the initial hit (low blow test) due to the bouncing hammer.

Different solutions have been established to prevent bouncing strikes of the hammer. Either, structural design of the loading fixture excludes bouncing strikes (stop block concept) or the rebounded hammer is caught after the first hit onto the specimen. Both options are not part of the experimental setup of the BAM drop tower test facility. Since bouncing strikes are not considered in serial testing, their influence on the data for crack resistance curve determination had to be investigated in advance. It had to be excluded that bouncing strikes cause additional, in terms of figures unknown amounts of crack growth while the corresponding work is not taken into account.

2.2.1. Experimental investigations

A series of DCI SE(B)25 specimens was tested at -40 °C in order to cover a broad range of stable crack extension Δa , Table 1.

The tests were performed with a sampling rate of 1 MHz and the whole loading history of the low blow hit and the following bouncing strikes was recorded. Only the first four loadings have been considered for further analyses. The force was measured by strain gages on the specimen and the load line displacement was captured by an electro-

optical camera. It cannot be excluded that the specimen slightly jumps sideways after the low blow hit. In this case, in the bouncing strikes, the hammer doesn't hit the specimen in the ligament area but eccentric so that the crack tip driving force is reduced due to a reduced bending moment. Simultaneously, the load line displacement signal of the camera may deteriorate since the focus point and distance change suddenly.

Table 1. Data of low blow tests on SE(B)25 specimens, DCI, -40 °C, yield loads are calculated acc. to ISO 12135 using the dynamic yield strength at -40 °C (a_0 – initial crack length, a_E final crack length, $a_{max0.1}$ and $a_{max0.25}$ – crack length at the standards Δa_{max} criterion of $0.1(W-a_0)$ and $0.25(W-a_0)$ resp.).

a_0/W	Δa in mm	a_E/W	$a_{max0.1}/W$	$a_{max0.25}/W$	Yield load in kN			
					with a_0	with a_E	with $a_{max0.1}$	with $a_{max0.25}$
0.50	0.62	0.52	0.55	0.62	20.00	18.08	16.20	11.25
0.49	2.31	0.59	0.54	0.62	20.18	13.46	16.34	11.35
0.49	2.61	0.60	0.54	0.62	20.40	12.88	16.52	11.47
0.49	3.32	0.62	0.54	0.62	20.44	11.19	16.56	11.50
0.48	0.43	0.49	0.53	0.61	-	-	-	-

2.2.2. Analysis of loading level

Fig. 5 displays the force-time records which have been isolated for the first four loadings (low blow test and three following bouncing strikes).

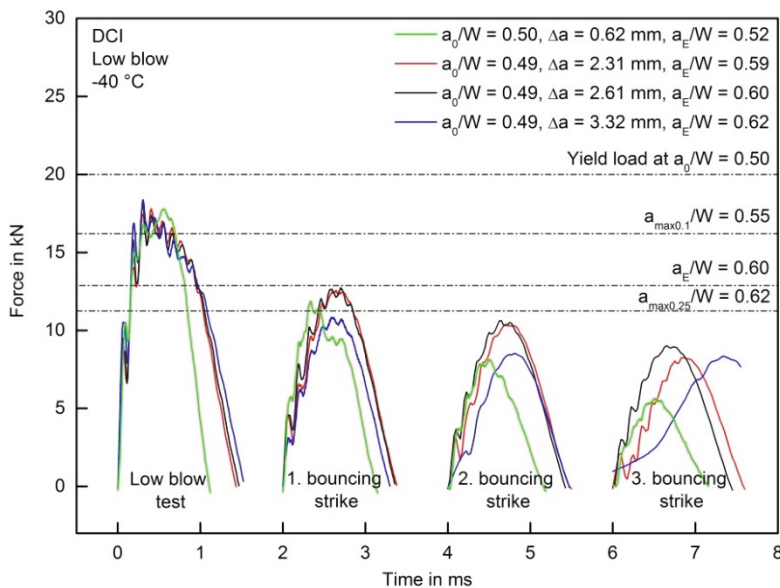


Fig. 5. Loading in the low blow test and following bouncing strikes (intervals between the loadings are not real for graphical reason).

The measured data show good reproducibility and expose that the loading in the low blow test is below the yield load at a_0/W . The same holds for the following bouncing strikes based on the yield loads calculated using the final crack length achieved in the tests.

2.2.3. Analysis of crack propagation sensor signal

The specimens were instrumented with crack propagation sensors which have been attached to the ligament, Fig. 6, so that the crack tip is located approximately next to the sixth wire from below. The failure mode of the crack propagation sensors is such that successive failure of the parallel single wires causes discrete jumps in the sensors voltage signal. This way crack growth can be monitored.

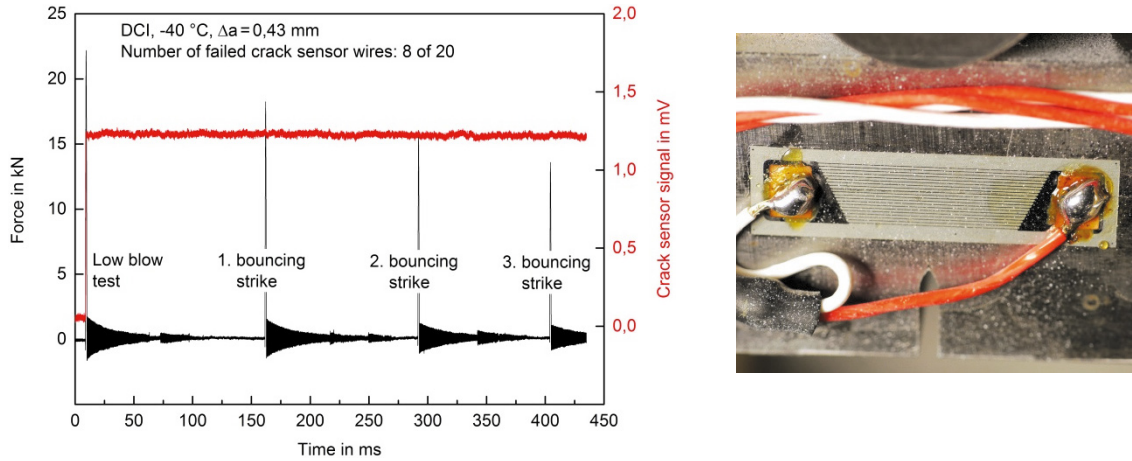


Fig. 6. Force and crack sensor signals in a low blow test and following bouncing strikes, $\Delta a = 0.43$ mm (left), crack propagation sensor (right).

With the specimen in Fig. 6 eight of 20 wires of the crack propagation sensor failed in the low blow test. As can be seen from Fig. 6, the signal of the crack propagation sensor remains constant after the low blow test. Therefore, it can be concluded that additional crack growth due to bouncing strikes does not occur. It should be remarked that there is a lower limit of discrete crack growth amounts of $200 \mu\text{m}$ which can minimally be detected by the used crack propagation sensor since that is the distance between the wires. Fig. 7(a) verifies the result of Fig. 6 for another specimen and points onto another effect which may happen during bouncing strikes, Fig. 7(b).

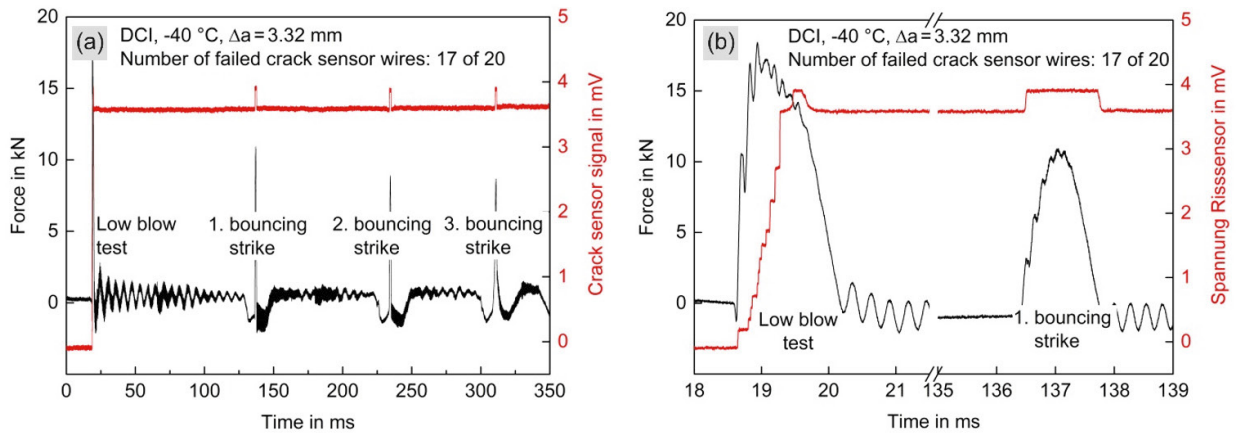


Fig. 7. (a) Force and crack sensor signals in a low blow test and following bouncing strikes, $\Delta a = 3.32$ mm, (b) detail from (a).

Fig. 7 shows that the crack sensor signal rises and subsequently decreases by one step at the end of the low blow test and in the following bouncing strikes as well. In between the signal level remains constant. This effect may happen at random and is due to a crack sensor wire which is just separated at the end of the low blow test. However, the subsequent elastic unloading of the specimen causes reformation of electric contact in the wire. This wire is then repeatedly opened and closed within the bouncing strikes.

2.2.4. Analysis of force-displacement records

Fig. 8 displays the force-displacement records of two specimens in the low blow test and the following bouncing strikes.

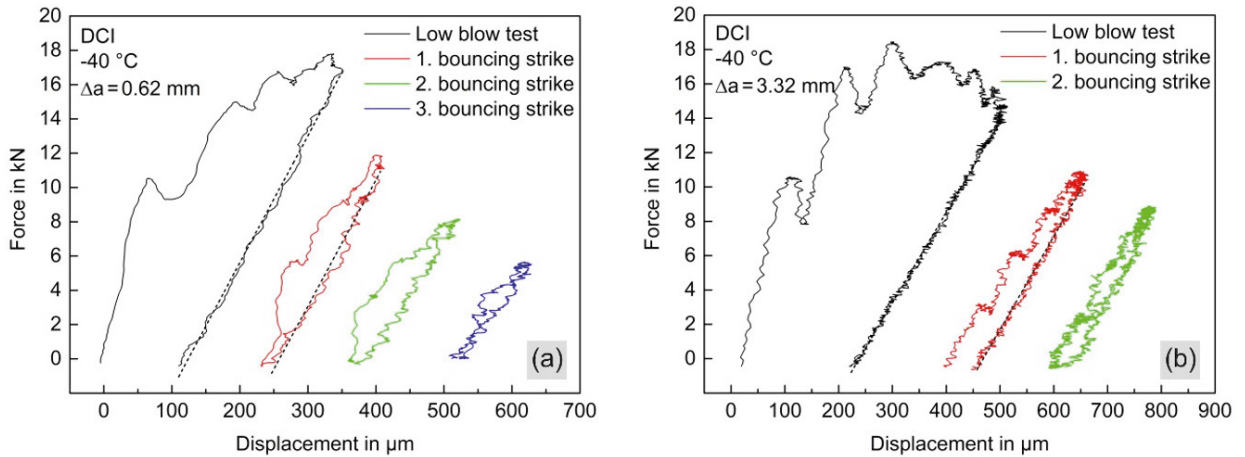


Fig. 8. Loading behavior of two specimens ((a) $\Delta a = 0.62$ mm and (b) $\Delta a = 3.32$ mm) in the low blow test and following bouncing strikes, (intervals between the loadings are not real for graphical reason).

It becomes clear from Fig. 8 that the loading behavior of the specimens in the low blow test differs significantly from that in the following bouncing strikes. The low blow test reveals elastic-plastic material behavior and distinct remaining plastic displacement corresponding to the achieved crack growth. On the other hand, the force-displacement records of the bouncing strikes reflect elastic material behavior. The displacement values at the beginning and after the bouncing strikes nearly coincide. Small deviations due to dynamic effects can be neglected.

Another measure to evaluate the loading behavior is the specimen stiffness. Table 2 summarizes specimen stiffness data deduced from the measured force-displacement records (see dashed lines in Fig. 8) by linear approximation of the unloadings after the low blow test and the first bouncing strike.

Table 2. Specimen stiffness data from unloadings after low blow tests on SE(B)25 specimens (see dashed lines in Fig. 8), DCI, -40 °C, R – correlation coefficient.

	Specimen with $\Delta a = 0.62$ mm		Specimen with $\Delta a = 3.32$ mm	
	Slope in kN/ μ m	R	Slope in kN/ μ m	R
Low blow test	0.074	0.997	0.053	0.998
1. bouncing strike	0.074	0.990	0.054	0.995

It can be seen from Table 2 that the stiffness values of the specimens (slope of the elastic unloadings) remain constant after the low blow test. Therefore, it can be concluded that the crack length remains constant as well.

2.2.5. Consequences of potentially unknown amounts of stable crack extension Δa

The consequences of potentially unknown amounts of stable crack extension Δa have been theoretically considered with respect to the J-R curve and crack initiation toughness, Fig. 9. The scenario is such that plastic work is done by bouncing strikes and this way additional crack extension is caused. In this case the corresponding amount of work would be unknown and not taken into account in the J-integral calculation, since data acquisition in low blow tests is generally limited to the first strike, i.e. the low blow test itself, Figs. 3 and 4. On the other hand, post-test crack length measurement on the specimens fracture surface does only provide one final crack extension value and cannot distinguish between parts due to low blow test or bouncing strikes, respectively. Consequently, the J-integral value provided by the low blow test would correspond to a slightly enhanced crack extension value instead of the true corresponding crack extension value. A crack resistance curve which would be constructed based on such multiple specimen data would slightly be shifted to the right, Fig. 9(a). The crack initiation toughness value which can be deduced would conservatively decrease slightly. The effect is reduced the flatter the slope of the J-R curve is. For instance, ductile cast iron materials show relatively flat J-R curves at -40 °C and dynamic loading so that the

consequences of the discussed effect would be of secondary importance. In case of a nearly horizontal J-R curve, the effects influence on the crack initiation toughness value would disappear, Fig. 9(b).

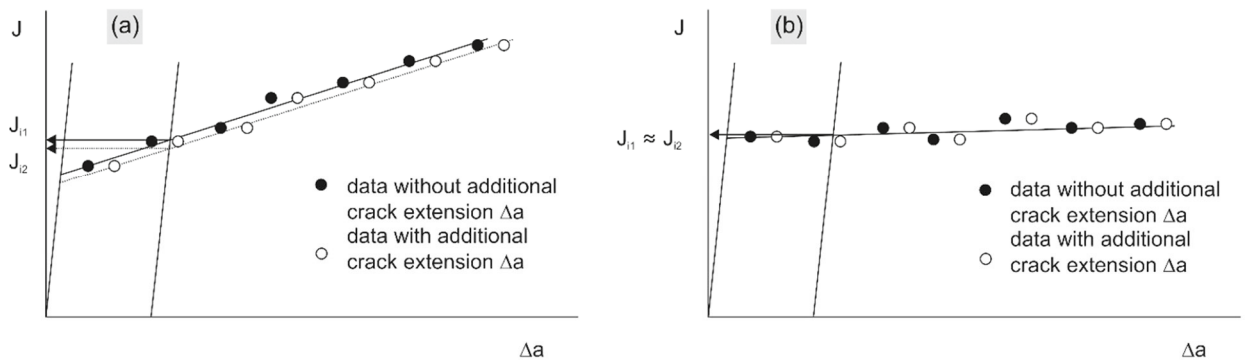


Fig. 9. Scheme on the influence of small amounts of additional crack extension on the multiple specimen J-R curve and the crack initiation toughness value, (a) material with steeper R curve, i.e. higher crack growth resistance, (b) material with flat R curve, i.e. very low crack growth resistance.

3. Summary

It can be concluded from the investigation of the crack propagation sensor signal, the force-displacement records and the loading level, that additional crack extension in the specimen due to bouncing strikes is not to be expected under the given conditions of test setup, material and loading. Therefore, it can be seen as a major experimental advantage that the striker does not have to be caught after the low blow test.

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