On the development of key curve methods for the determination of dynamic crack resistance curves of ductile cast iron (DCI)

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Abstract. The present paper reports on the further development of fracture mechanics test methods for ductile cast iron (DCI) within an ongoing research project. An analytical approach (compliance ratio method, CR) as well as a numerical method (finite element analysis, FE) have been comparatively investigated as key curve methods for the determination of dynamic crack resistance curves on PCVN and SE(B)15 specimens at room temperature and -40 °C. An experimental reference data base was set up by low blow multiple specimen testing for determination of dynamic crack resistance curves. Along with detailed investigations on the influence of test temperature, microstructure, loading rate and specimen geometry on the fracture behaviour of the DCI tested were performed in order to link these parameters with the fracture mechanical properties. This paper is focussed on CR method results only. The present results show that the CR method is suited to provide valid dynamic crack resistance curves for both specimen types. Nevertheless, handling and accuracy are better with SE(B)15 specimens.

Introduction

Currently, dynamic crack resistance curves of DCI still can only be determined by time and material extensive multiple specimen techniques like low blow or stop block. But the problem of how to provide dynamic material properties (like dynamic crack initiation toughness) as efficient as possible becomes more and more severe taking modern design criteria for crash scenarios into consideration where fast changes of the stress and strain state in the component take place due to dynamic loading. Therefore, an analytical approach (compliance ratio method, CR) as well as a numerical method (finite element analysis, FE) are comparatively investigated as key curve methods for the determination of dynamic crack resistance curves on precracked Charpy specimens (PCVN) and single edge bend specimens (SE(B)15) at room temperature (RT) and -40 °C. The present paper reports on the current status of the further development of the relevant fracture mechanics test methods and is focussed on the CR methods results only.

Material

The material under investigation was cut from a DCI block of the dimensions 2000 x 500 x 160 mm which had been casted in sand according to a material specification of transport and storage containers for nuclear material. The microstructure was ferritic with 3 % of pearlite. Table 1 gives an overview on the mechanical properties in dependence on temperature and strain rate. Fig. 1 displays the flow curves at RT and -40 °C in dependence on the strain rate. Analogously to steels, strength increases and ductility decreases for increasing strain rate. The fracture surfaces of specimens tested in dynamic tension tests at -40 °C exclusively show cleavage fracture.

Table 1. Strength and ductility values of the investigated DCI (mean values)

Strain rate in s^{-1}	Temperature in °C	0.2-proof stress in MPa	Ultimate tensile strength in MPa	Elongation at rupture in %	Reduction of area in %
0.0002	80	222	344	18.0	21
	RT	246	376	23.0	23
	-40	281	408	16.5	19
0.01	80	244	360	20.0	20
	RT	267	380	18.0	20
	-40	307	417	14.0	18
1	80	282	380	17.0	23
	RT	314	415	21.0	20
	-40	359	457	17.0	20
100	RT	388	466	15.0	19
	-40	428	501	15.0	9
400	RT	395	487	16.5	15
	-40	443	506	22.0	8

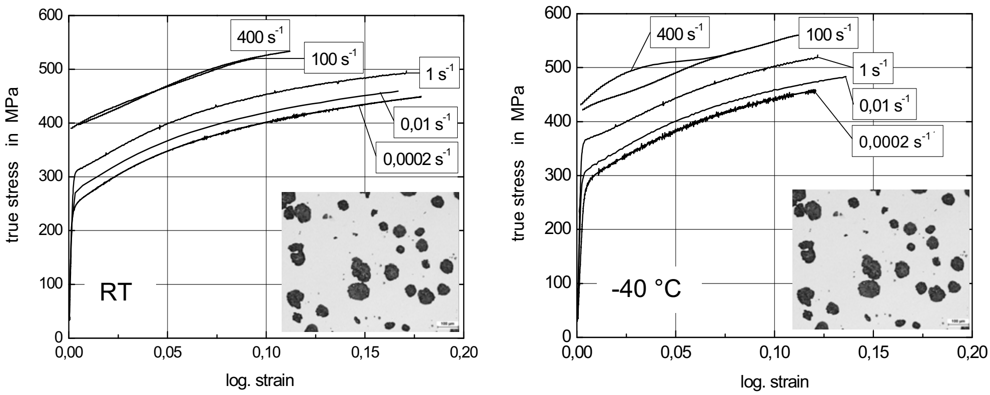

Figure 1. Influence of strain rate on the flow curves at RT and -40 °C

Compliance Ratio (CR) Method

The CR method proposed by Candra et al. [1] is an analytical approach to determine the current crack length in single specimen tests for crack resistance curve determination. More relevant details can be taken from [1,2]. The method is based on the prerequisite that the key curve of a so called source specimen is equal to the target specimen ones. At first, a source specimen is tested quasistatically using the unloading compliance method and a force-displacement curve without crack growth is extracted by a fairly simple procedure. This curve is normalised by the maximum force value and the corresponding displacement in order to get the key curve. Then, in several steps, the key curve is used to determine the compliance and hence the crack length of dynamically tested target specimens. The force-displacement record is the only information needed from the target specimen. Final crack length or other calibration data are not necessary.

Quasistatic and Dynamic Fracture Mechanics Investigations and Results

Five quasistatic crack resistance curves at RT have been determined by unloading compliance method with 20 %-sidegrooved PCVN as well as SE(B)15 specimens (source specimens), Fig. 2.

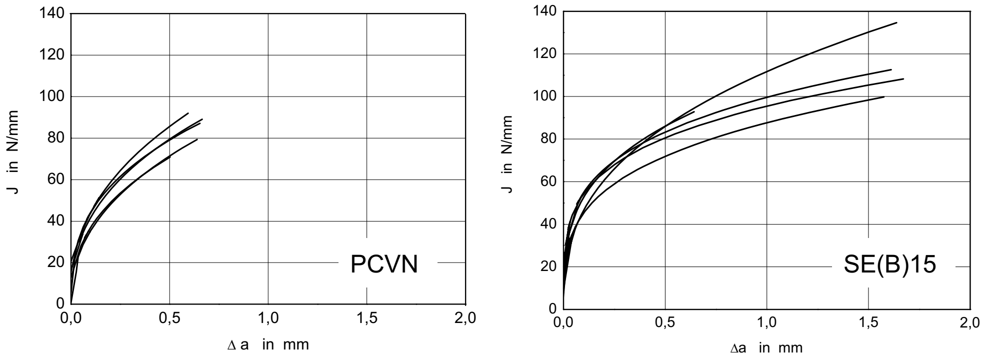

Figure 2. Quasistatic crack resistance curves at RT according to ASTM E 1820 for sidegrooved PCVN and SE(B)15 source specimens

The low blow multiple specimen technique was used to generate dynamic reference crack resistance curves for PCVN and SE(B)15 specimens at RT and -40 °C. Approximately 20 specimens were tested for each type and temperature in order to get well characterized references, Fig. 3.

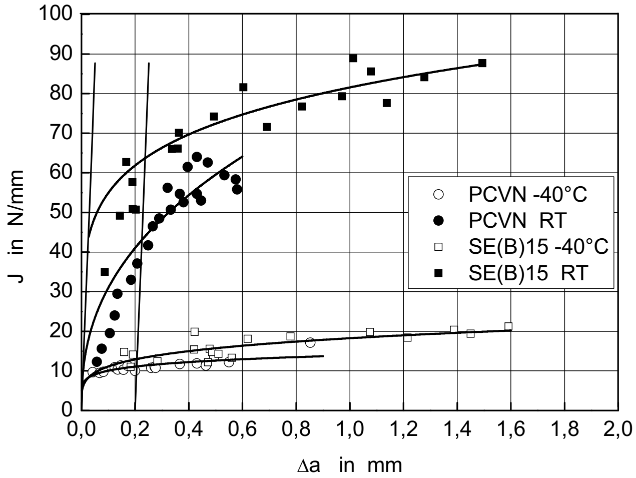

Figure 3. Dynamic reference crack resistance curves for sidegrooved PCVN and SE(B)15 specimens acc. to ASTM E 1820 at RT and -40 °C

The PCVN specimens were tested with a 7.5 J hammer on an 50 J Charpy pendulum impact machine and the SE(B)15 specimens on a drop tower. Initial height and impact mass of the drop tower were adapted that way that all tests in both test systems could be performed within a uniform range of loading speed of approximately $6{\cdot}10^4$ to $2{\cdot}10^5$ MPa√m/s.

The quasistatic and dynamic technical J_{Ic} crack initiation toughness data derived from the crack resistance curves are listed in Table 2.

Table 2. Quasistatic and dynamic technical J_{Ic} crack initiation toughness data (ASTM E 1820)

Specimen	Temperature in °C	Quasistatic loading, J_{Ic} in N/mm	Dynamic loading, J_{Ic} in N/mm
PCVN	RT	64	45
	-40	-	11
SE(B)15	RT	71	65
	-40	-	13

It follows from Fig. 2 and Table 2 that both specimen geometries provide comparable fracture toughness results with quasistatic loading at RT. A significant influence of specimen geometry cannot be detected.

Fig. 3 clearly shows the significant influence of temperature on the dynamic crack resistance behaviour. Thereby it has to be distinguished between crack initiation and crack extension. The course of the datum points in the initiation region in Fig. 3 indicates that the physical crack initiation is almost independent from temperature. But if technical crack initiation toughness values like J_{Ic} acc. to ASTM E 1820 are deduced, significant differences between RT and -40 °C can be noticed, see also Table 2. The crack growth resistance at -40 °C is extremely reduced compared to RT as it is indicated by the course of the crack resistance curves after initiation.

Taking the scatter into account, remarkable differences between the dynamic PCVN and SE(B)15 R-curves at -40 °C cannot be noticed. Nevertheless, the dynamic crack resistance curve of SE(B)15 specimens at RT lies above the level of the smaller PCVN specimens. This aspect is still under investigation.

Another feature of Fig. 3 is worth to be mentioned. If the material data is fitted by a power law function according to the ASTM E 1820 procedure, the experimentally determined crack resistance behaviour can only be described inadequately in the range of physical crack initiation which is especially important for component safety assessment.

At RT quasistatic and dynamic R-curves can be compared for both, PCVN and SE(B)15, Fig. 2 and 3 and Table 2. If the scatter bands are taken into account the dynamic R-curves of PCVN are slightly lower than with quasistatic loading. With SE(B)15 there are no significant differences.

Damage and fracture behaviour of DCI

Since there was not expected cleavage fracture even observed on the fracture surfaces of dynamic tensile specimens as well as fracture mechanics specimens at RT, some supplementary tests at 80 °C were performed in order to comparatively investigate the fracture behaviour on the upper shelf of toughness too.

Systematic metallographic as well as fractographic microstructural analyses have been performed accompanyingly throughout the whole test program. There are extensive results for the investigated specimen geometries and loading conditions which focus on the material specific damage and fracture behaviour. Fig. 4 has been developed for systematization and summarizing visualization. Fig. 4 provides a systematics of damage and fracture behaviour of DCI taking loading type, loading rate, specimen geometry and test temperature into account that has not been available before in such detail.

This time, only some aspects of Fig. 4 can be highlighted. The fracture surfaces of dynamically tested tensile specimens at -40 °C exclusively show cleavage fracture in the matrix. Nevertheless, pronounced features of ductile damage like debonding of nodules and void growth in the microstructure close behind the fracture surface can still be observed there. Fracture mechanics specimens dynamically tested at -40 °C do also show cleavage fracture surfaces exclusively. However, due to enhanced stress triaxiality, the ductile damage is here reduced to slight debonding.

On the other hand, the dynamic force-displacement records at -40 °C show a typical upper shelf appearance without pop ins or unstable failure.

This contradiction between the fracture mechanism and the qualitative macroscopic appearance of the force-time record seems to be explicable by the following considerations. After initiation, the crack propagates by cleavage mechanism through the small ferritic matrix areas, which measure only one or a few grains. But each time the crack runs into the next graphite nodule the crack tip is blunted significantly by the shape of the nodule and shortly more or less arrested. This way, a lot of microscopic pop ins superimpose and cause a macroscopic elastic-plastic appearance of the force-time record, where single pop ins cannot be observed. Consistently, the corresponding dynamic R-curves at -40 °C only show a very low remaining crack growth resistance, Fig. 3.

Results of the CR method

All low blow specimens have been analysed as single specimen fracture mechanics tests by means of the CR method. Figs. 5 and 6 show the dynamic R-curves determined this way compared to the dynamic reference R-curves. It can be seen that the reference R-curves lie in between the scatter bands of the single specimen R-curves. The results of the CR method have been verified by comparison of calculated and measured crack length values, Figs. 7 and 8. Figs. 7 and 8 show that the corresponding tolerance criteria valid for quasistatic testing are fulfilled here with dynamic testing too. Concluding from Figs. 5 to 8 it can be stated that it seems to be possible to determine a dynamic crack resistance curve for DCI with reasonable accuracy by means of testing only few specimens.

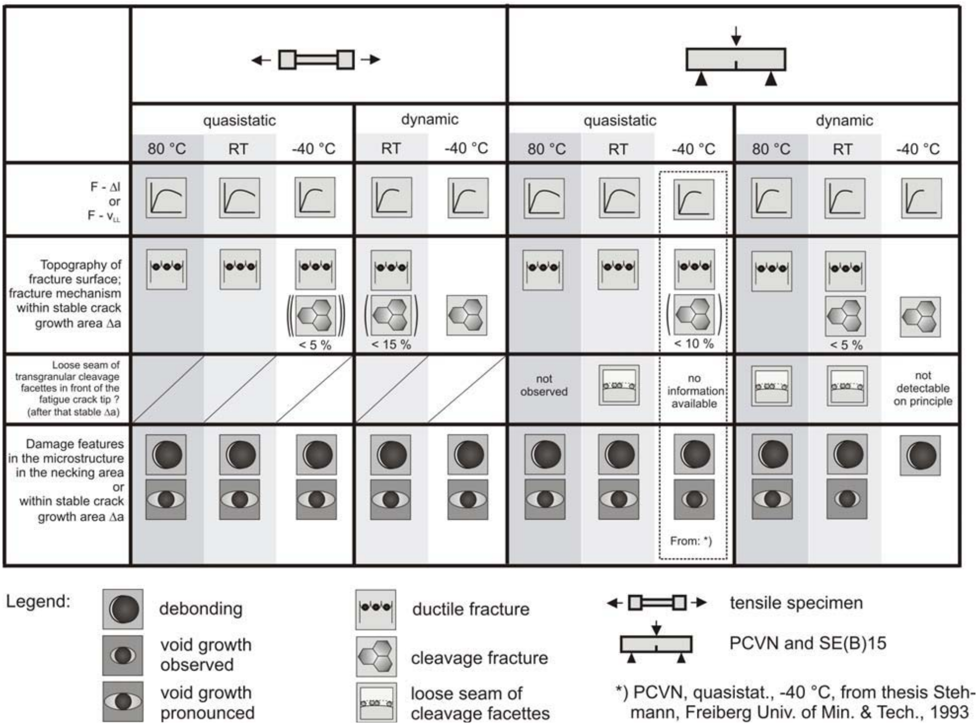

Figure 4. Systematics of damage and fracture behaviour of DCI in tensile and fracture mechanics tests

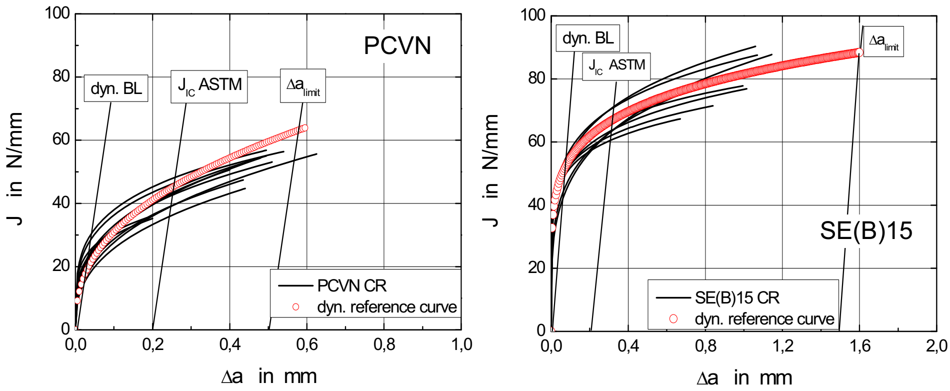

Figure 5. Comparison of dynamic CR method R-curves and reference R-curves at RT

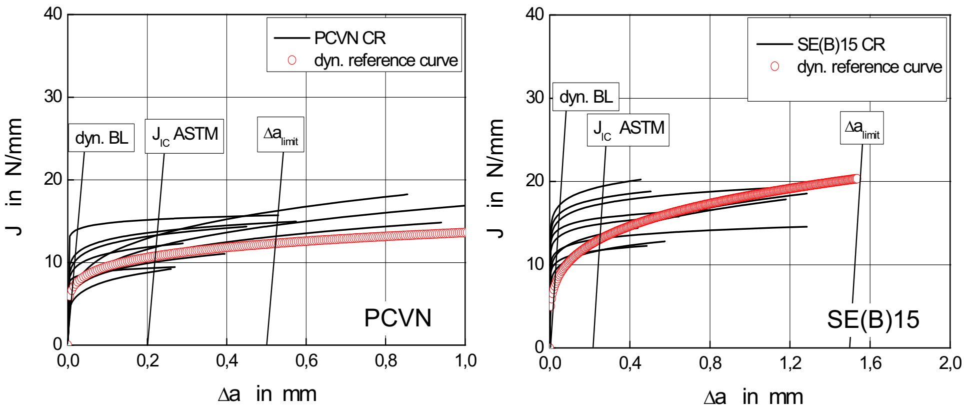

Figure 6. Comparison of dynamic CR method R-curves and reference R-curves at -40 °C

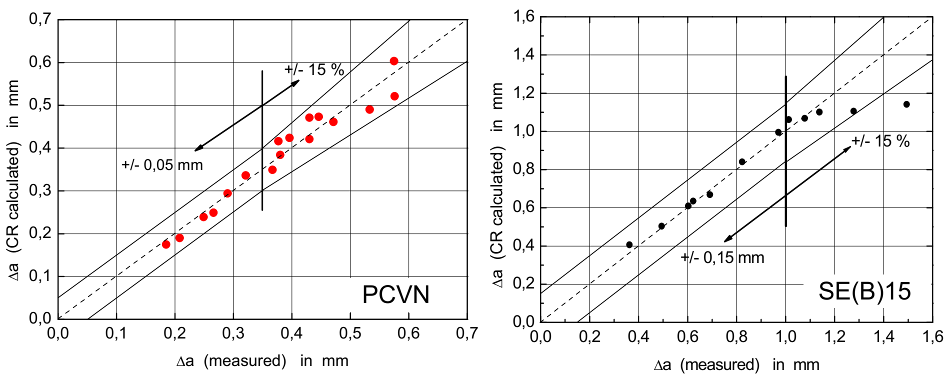

Figure 7. Comparison of calculated and measured crack length at RT

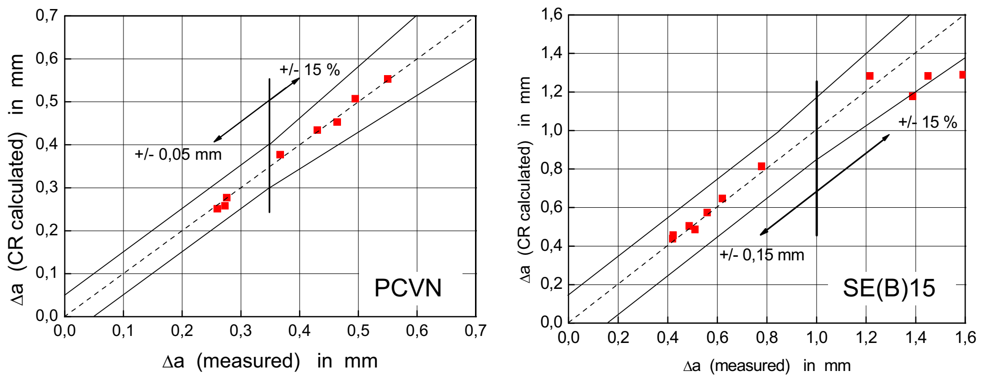

Figure 8. Comparison of calculated and measured crack length at -40 °C

Conclusions and Outlook

Concluding from the test series performed, SE(B)15 specimens are regarded to have a strong advantage over PCVN with respect to their potential to provide a representative and reliable characterization of DCI by dynamic R-curves.

In spite of the slightly higher material demand of SE(B)15 specimens they still can be regarded as small specimens with very good handling. SE(B)15 specimens offer the advantage that remarkably higher forces have to be measured. Due to the strain gage instrumentation on the SE(B)15 specimen itself the force signals show much less ringing compared to PCVN specimens tested in instrumented Charpy pendulum impact machines. This makes SE(B)15 more suited for key curve analysis where signals of high quality are important, though strain gage instrumentation makes a test more complex. Furthermore, the more accurate and reliable force data of SE(B)15 make it generally possible or improve the chances to gain important information on the fracture behaviour as for instance on pop ins. Another advantage of SE(B)15 should not be underestimated. DCI material inherent measuring uncertanties, e.g. with fractographic crack length measurement, are relatively of less consequence with SE(B)15 due to their larger crack length validity ranges than with PCVN. Finally, SE(B)15 specimens have a better capability to integrate over local material inhomogeneities because of the bigger material volume tested.

At present there is phase II of the research project running. The investigations for application and further development of the key curve method are limited to SE(B)15 specimens and focussed on a second, highly praxis relevant DCI material with 10 to 20 % of pearlite.

Acknowledgement

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