THE IMPACT OF DUCTILE CAST IRON FRACTURE BEHAVIOUR ON DYNAMIC FRACTURE MECHANICS R-CURVE TESTING USING KEY CURVE METHODS

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ABSTRACT

Dynamic fracture mechanics characteristics are required for design and safety proof of advanced ductile cast iron (DCI) components. In this paper, the analytical compliance ratio (CR) and numerical finite element (FE) key curve methods were investigated for dynamic R-curve testing. Two DCI materials, a purely ferritic and a ferritic one with 18 % of pearlite, were tested at room temperature (RT) and -40 °C. The special focus is on the impact of the materials damage and fracture behaviour on performance and limitations of the investigated methods.

Systematic metallographic and fractographic microstructural analyses were performed accompanying the test program. Summarizing systematics of the specific damage behaviour and fracture mechanisms were developed taking microstructure, loading rate, specimen geometry and test temperature into account.

There has been a change from ductile to brittle fracture mechanism observed at -40 °C with ferritic DCI and even at RT with ferritic-pearlitic DCI. The ferritic-pearlitic DCI did not show R-curve behaviour at -40 °C and only single J_{uc} values could be determined. Furthermore, with ferritic-pearlitic DCI, random pearlite shares in the ligament caused the relation between loading rate, force-deflection record and crack extension not to remain uniquely defined. Therefore, the FE key curve method proofed not to be applicable since the FE model was based on homogeneous isotropic material and ductile failure mode only. The analytical CR key curve method worked well only with selected combinations of microstructure, specimen geometry and temperature.

In summary it has to be concluded that a robust, accurate and sufficiently simple dynamic key curve method that was suited for application in quality control of industrial relevant DCI qualities cannot be provided currently.

KEYWORDS

Ductile cast iron, key curve, dynamic crack resistance curve, damage and fracture behaviour

INTRODUCTION

Establishing of dynamic DCI material properties (e.g. dynamic crack initiation toughness or fracture toughness) effectively and as efficiently as possible becomes increasingly a prime requirement since modern design and safety criteria for components require such fracture mechanics key values (e.g. [1-2]). Outstanding examples of advanced ductile cast iron components are heavy casks for transport and storage of radioactive materials. Therefore, the latest results of BAM investigations on dynamic fracture mechanics R-curve testing on DCI using key curve methods are briefly summarized in this paper. As reported in previous papers in detail [3-4], the analytical compliance ratio (CR) originally proposed by Candra et al. [5] and numerical finite element (FE) key curve methods had been rated potentially most suited for determination of crack length values within dynamic R-curve testing on DCI. Now, the experimental and numerical investigations had been finalised recently. Summing up, the special focus of this paper is on the impact of the materials damage and fracture behaviour on performance and limitations of the investigated dynamic key curve methods.

MATERIALS AND MECHANICAL-TECHNOLOGICAL PROPERTIES

Two EN-GJS-400 materials (German designation for a DCI grade) which are relevant for technical applications as mentioned above were investigated at room temperature and -40 °C. Fig. 1 shows the microstructures of the purely ferritic and the ferritic one with 18 % of pearlite.

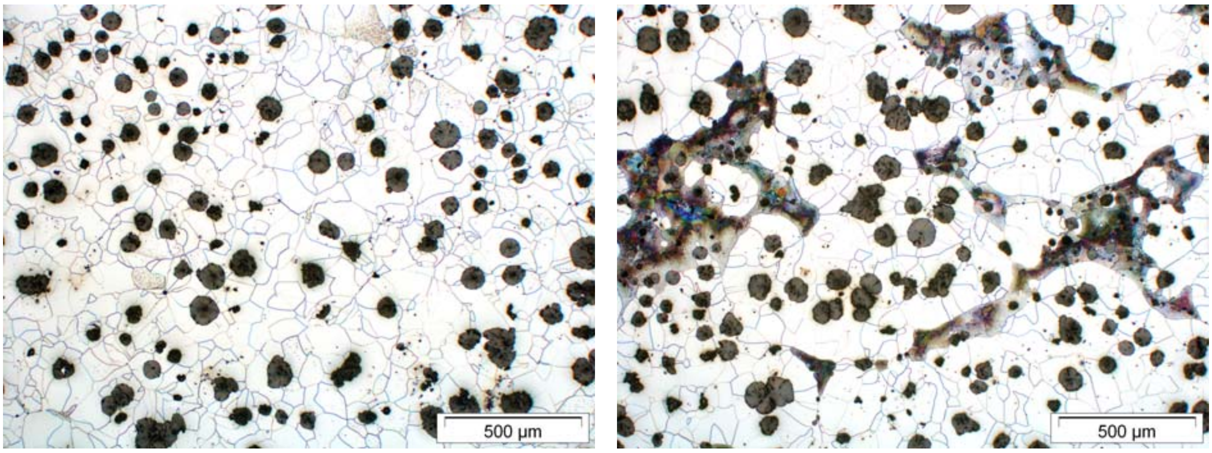


Fig. 1: Microstructure of ferritic EN-GJS-400 (left) and ferritic-pearlitic EN-GJS-400 with 18 % of pearlite (right)

Since there was not expected cleavage fracture observed on the fracture surfaces of dynamic tensile specimens as well as fracture mechanics specimens of the ferritic grade at RT, some supplementary tests at 80 °C were performed in order to comparatively investigate the fracture behaviour on the upper shelf of toughness. As shown in Fig. 2, transition behaviour can be observed at RT for both materials in Charpy tests.

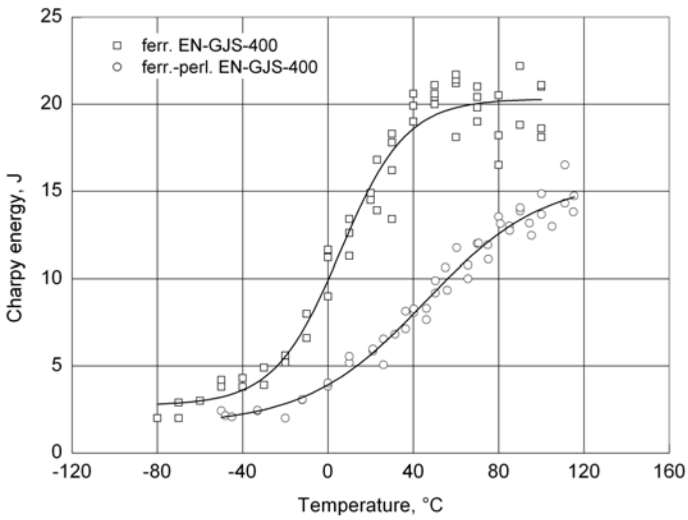


Fig. 2: Charpy energy vs. temperature curves

Figs. 3 and 4 illustrate the stress-strain behaviour of the materials in dependence on the strain rate.

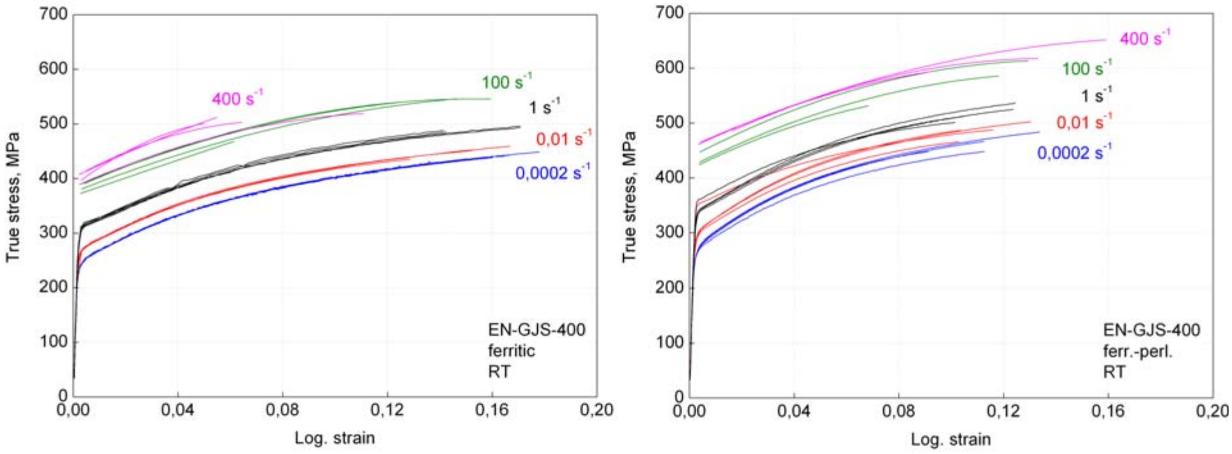


Fig. 3: Flow curves at RT

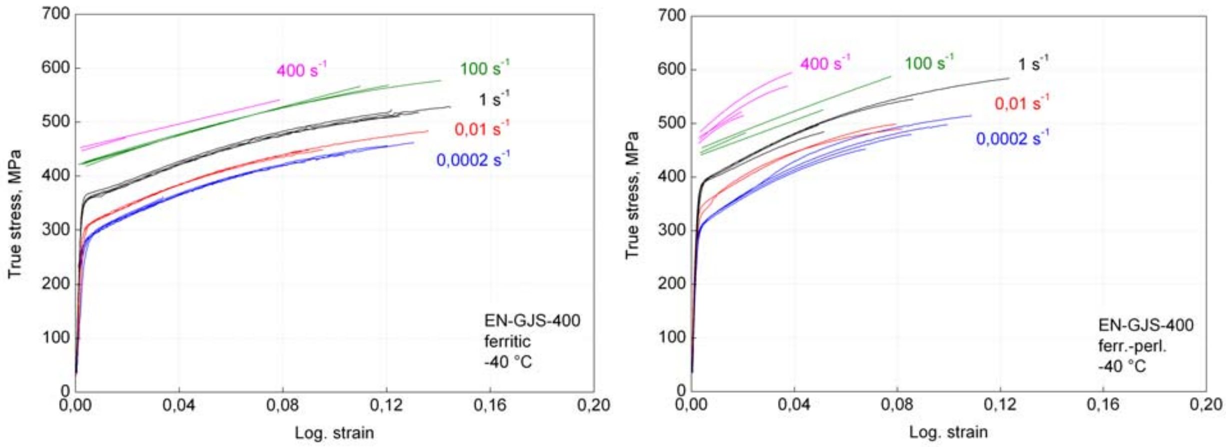


Fig. 4: Flow curves at -40 °C

It can be concluded from the tensile tests that strength moderately increases with decreasing temperature while it significantly rises with increasing strain rate. Simultaneously, elongation at rupture is significantly reduced by increasing strain rate and decreasing temperature.

EXPERIMENTAL DYNAMIC FRACTURE MECHANICS INVESTIGATIONS

With ferritic EN-GJS-400 dynamic reference crack resistance curves were determined simultaneously for PCVN and SE(B)15 specimens by means of the low blow multiple specimen technique at RT and -40 °C, Fig. 5. A lesson learnt from these investigations was that SE(B)15 specimens can be rated the preferred specimen type and offer several advantages [4]. Therefore, the tests with ferr.-pearl. EN-GJS-400 were run with SE(B) specimens only. At -40 °C ferr.-pearl. EN-GJS-400 did not show R-curve behaviour but pop-ins and brittle fracture. All 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 so 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. Due to instrumentation each single low-blow specimen test was at disposal for key curve analysis.

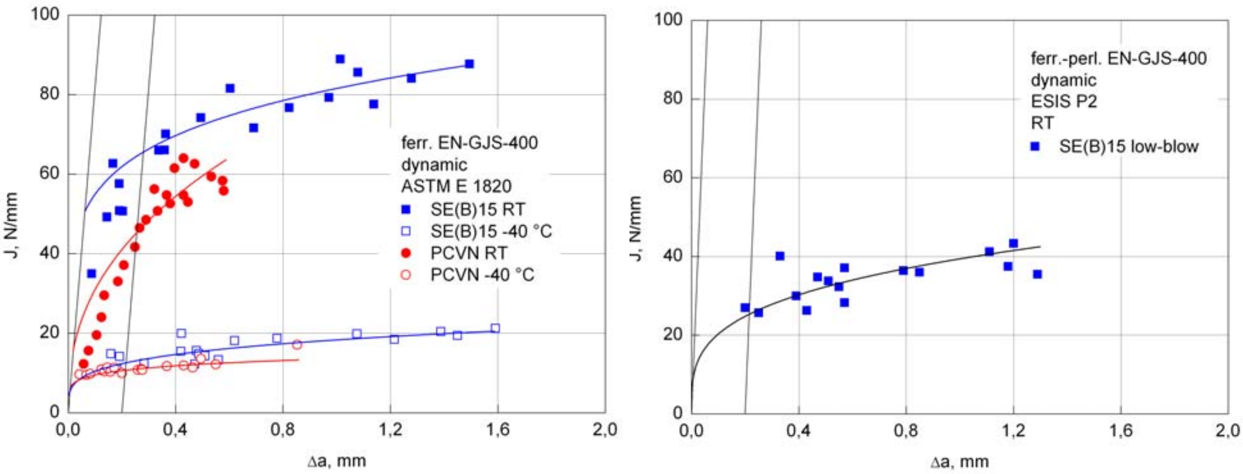


Fig. 5: Dynamic reference R-curves by low-blow multiple specimen technique for ferr. EN-GJS-400 (left) and ferr.-perl. EN-GJS-400 (right)

INVESTIGATED KEY CURVE METHODS

The principle as well as materialspecific features of the analytical CR key curve method are reported in detail in [3-5]. Basic procedure of the FE key curve method is that the experimental force-displacement record is superimposed by a numerically determined set of force-displacement-curves with different but constant crack length (key curves). These curves were generated by simulation of the dynamic fracture mechanics tests on PCVN and SE(B)15 specimens using 2d-models within the FE code ABAQUS. Strain rate and temperature dependence of the materials mechanical properties were accounted for by incremental plasticity based on the implemented experimental sets of flow curves for RT and -40 °C and 5 different strain rates.

DAMAGE AND FRACTURE BEHAVIOUR OF EN-GJS-400

The fracture behaviour of EN-GJS-400 is governed by its microstructure. In the present investigations the focus was not on the influence of the graphite morphology but on the metallic matrix. The key issue was the question of how far the crack resistance behaviour is influenced by technically relevant pearlite shares in the ferritic matrix and how does this influence the applicability of the key curve methods.
Systematic metallographic as well as fractographic microstructural analyses using optical microscope and SEM had been performed throughout the test program. The results are bulky and very detailed. Therefore, the graphics in Fig. 6 have been developed for schematic systematization and summarizing visualization. These graphics provide systematics of damage and fracture behaviour of EN-GJS-400 taking microstructure, loading type, loading rate, specimen geometry and test temperature into account that has not been available before in such complexity. Unfortunately, Fig. 6 cannot be discussed in detail here as well as corresponding microstructural images cannot be shown. Only some aspects can be highlighted.
Pearlite has a detrimental effect on both, ductility and toughness. Basically, this is known, but the observed extent is surprising with respect to the relative low pearlite share of 18 %.
The fracture surfaces of dynamically tested tensile specimens of both, ferritic and ferritic-pearlitic EN-GJS-400, exclusively show cleavage fracture in the matrix at -40 °C. Nevertheless, pronounced features of ductile damage like debonding of nodules and void growth in

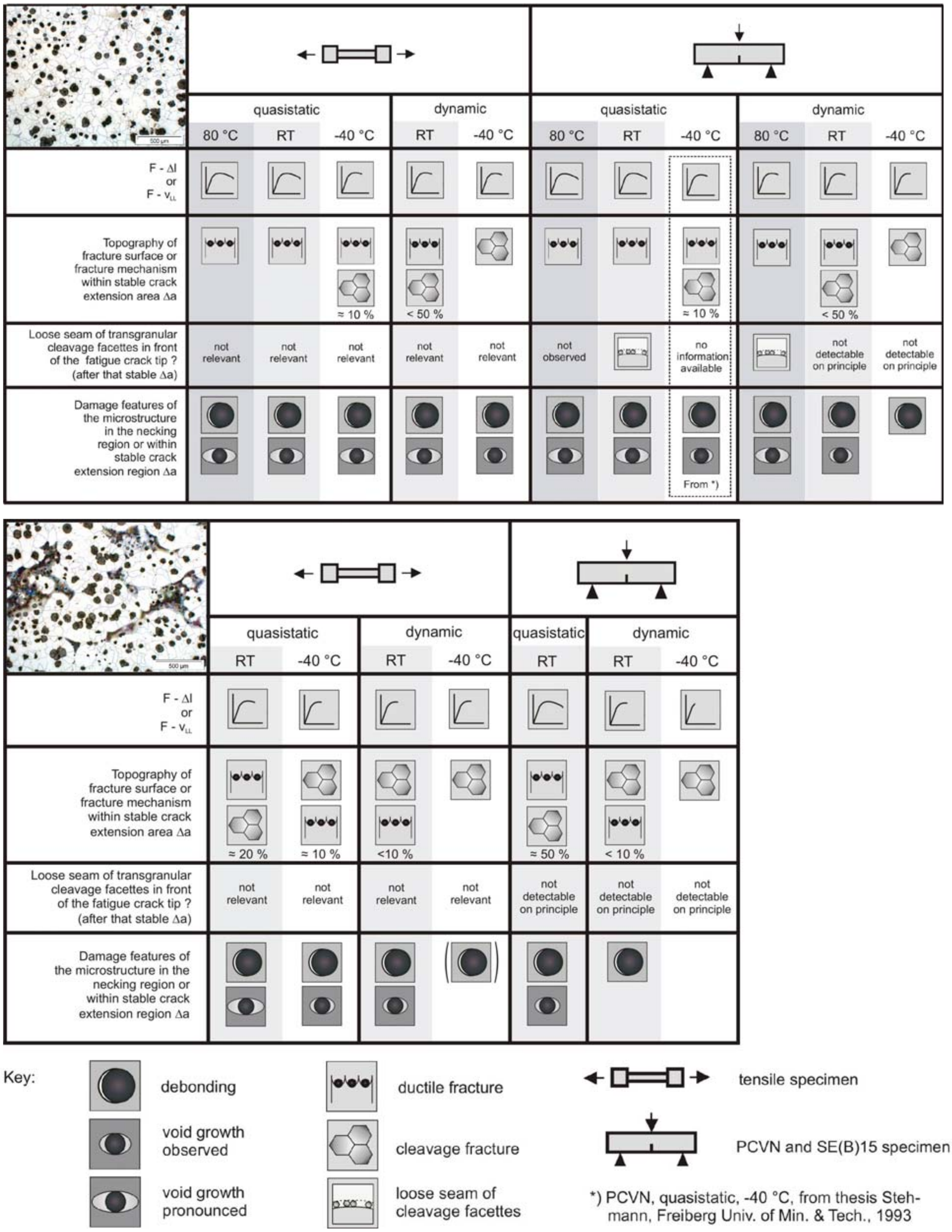


Fig. 6: Damage and fracture behaviour of DCI taking microstructure, loading type, loading rate, specimen geometry and test temperature into account

the microstructure close behind the fracture surface can still be observed with the ferritic grade only.
Ferritic 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 reduced further to only moderate debonding. On the other hand, the dynamic force-displacement records at -40 °C show continuous upper shelf appearance without pop ins or unstable failure as it could be expected from the morphology of the fracture surface. This contradiction between fracture mechanism and 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. Each time when the crack runs into the next graphite nodule the crack tip is blunted significantly due to the spheric shape of the particle and it is more or less arrested within a short time. Thus, a number of microscopic pop ins are superimposed 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. 5.
With dynamic fracture mechanics specimens of ferritic-pearlitic EN-GJS-400 at -40 °C, plasticity is reduced to an extent where ductile damage and upper shelf R-curve behaviour vanished, pop ins appeared and only single J_{uc}-values could be determined.

PERFORMANCE AND LIMITATIONS OF THE KEY CURVE METHODS

Due to the microscopically heterogeneous microstructure of EN-GJS-400, the application of key curve methods basically requires to test more simultaneous specimens as used with steel in order to get reproducible results. Oscillations in the signals of the measured quantities cannot be avoided totally due to the dynamic nature of the tests but they were reduced by optimization of the test setup. In order to make the data suited for key curve analysis they were smoothed by an appropriate FFT procedure always regarding not to distort the materials behaviour. Another feature is typical for dynamic fracture mechanics tests on EN-GJS-400 and it makes the key curve analysis even more difficult. Especially short duration of a single test is observed due to comparatively limited toughness and thus data analysis might be limited to only few oscillations.

FE key curve method

With both materials it is observed at all but one of the investigated loading conditions (strain rate, temperature) that the FE key curve method fails in superimposing the set of key curves with the experimental force-displacement record. Either no or not enough intersection points are obtained. The method was only applicable with ferritic EN-GJS-400 at RT. But there, the precision of the crack length values predicted did not comply to the requirements. This result is mainly due to the basic procedure of the FE key curve method where the elastic-plastic material behaviour is modelled according to temperature and strain rate dependent flow curves. This policy does not allow to account for changes in the microscopic damage and fracture mechanisms as they appeared in the investigated range of strain rate, temperature and microstructure, Fig. 6. Another aspect is the large scatter of the force-displacement records of ferr.-pearl. EN-GJS-400, Fig. 7. The reasons are pearlite shares influencing the fracture behaviour. The pearlite is randomly distributed and may be positioned specifically in single specimens in the ligament in front of the crack tip. Fig. 7 reveales that the relation between loading rate, force-displacement record and crack extension is not uniquely defined in case of non-isotropic material like randomly spaced pearlite shares. These features of real

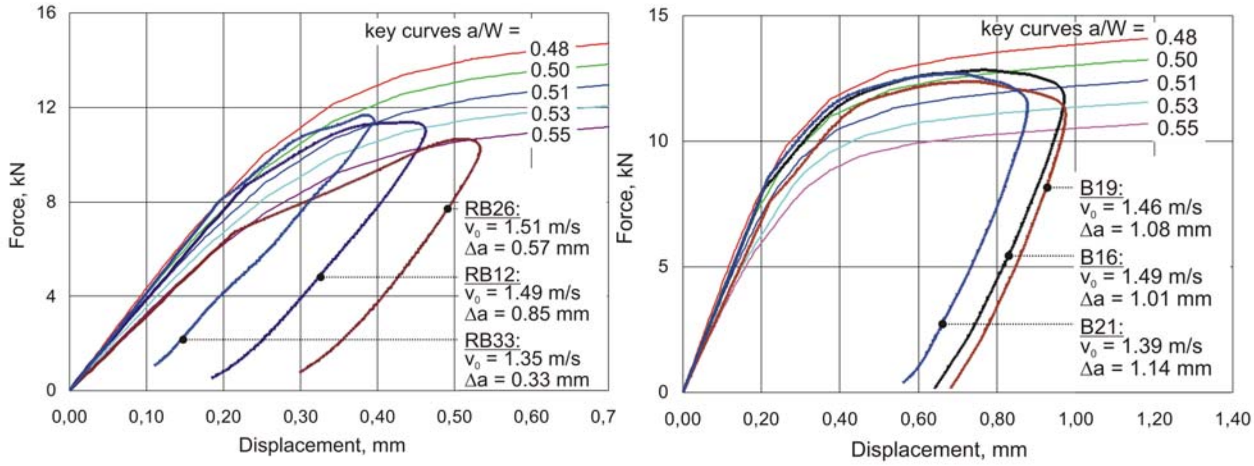


Fig. 7: FE key curves and experimental force-displacement records of sets of specimens tested at comparable loading rates at RT, left: ferritic EN-GJS-400, right: ferritic EN-GJS-400

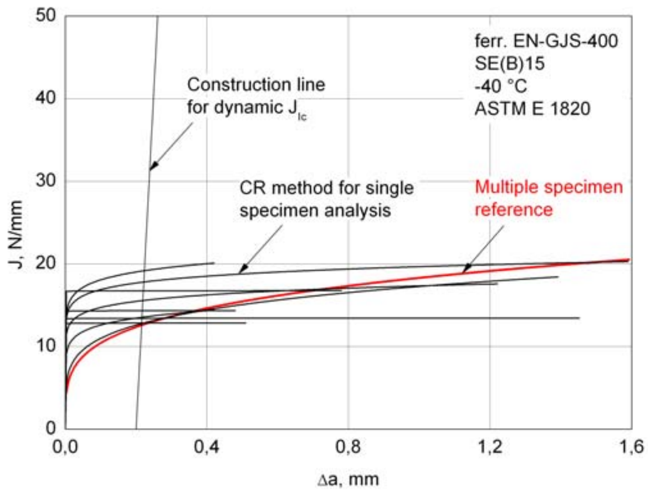
microstructure behaviour cannot be covered by the FE simulation practised where isotropic and homogeneous material properties are basically required.
It can be concluded that the investigated FE key curve method was not successfully applicable due to the described materialspecific damage and fracture behaviour, scatter in the local material properties as well as imperfect precision in the prediction of crack length values.
An option to enhance the FE model could be to implement damage models including both, ductile and brittle fracture, and thus covering the described material behaviour of EN-GJS-400. Part of such type of simulation should also be a consideration of the real microstructure. Nevertheless, an upgrade of the FE simulation by these measures would go along with significantly enlarged efforts. The FE model would become highly sophisticated. This would be in contradiction to a key objective of the present research to provide a key curve method as robust and simple as possible. Therefore, this option had not been part of the present investigations.

CR key curve method

The CR key curve method proofed to be basically applicable with all test conditions and materials where R-curve behaviour was observed. An important finding is that it is not sufficient to compare the R-curve generated via key curve to the reference R-curve. Rather it is necessary to additionally check the calculated crack length values against the real values measured on the fracture surface in order to avoid misinterpretations. This is a clear materialspecific disadvantage, since actually, measured crack length values need not to be addressed within the CR method. Considering these limiting conditions, reasonable precision of CR method results was found only for PCVN as well as SE(B)15 specimens at -40 °C. Graphical examples are shown in Fig. 8 and Fig. 9.

CONCLUSIONS

The results allow for a distinctive assessment of the suitability of the investigated key curve methods for the determination of dynamic J-R-curves of EN-GJS-400. This is briefly summarized here.
The FE method did not successfully work due to microstructurally related changes in the damage and fracture behaviour of EN-GJS-400 as well as scatter in the local material properties. These features are not covered by the FE model used.



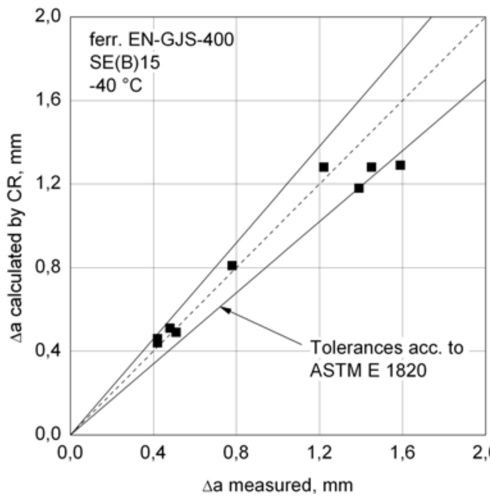


Fig. 8: Comparison of CR single specimen R-curves with reference R-curve

Fig. 9: Comparison of CR-calculated and measured crack lengths

It has been identified that the CR method only worked with sufficient precision for ferritic EN-GJS-400 at selected combinations of the parameters specimen geometry and test temperature. Nevertheless, a systematics could not be identified at this.
Therefore, it is concluded that a robust, accurate and sufficiently simple dynamic key curve-method that is suited for application in quality control of industrial relevant EN-GJS-400 qualities cannot be provided currently.

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