Fracture Mechanics Safety Approaches

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30th MPA-Seminar in conjunction with the 9th German-Japanese Seminar
Stuttgart, October 6 and 7, 2004

Abstract

Component integrity assessments require the knowledge of reliable fracture toughness parameters characterising the initiation of the failure process in the whole relevant temperature range. From a large number of fracture mechanics tests a statistically based procedure was derived allowing to quantify the initiation of fracture toughness as a function of temperature as a closed function as well as the temperature dependence of the cleavage instability parameters. Alternatively to the direct experimental determination one also can use a correlation between fracture toughness and notch impact energy.

Key words: ductile crack initiation, cleavage instability, failure, notch impact energy, fracture toughness-Charpy-correlation.

1 Introduction

The well established engineering methods to determine allowable component loadings are based on the fundamental equation of the strength analysis:

$$\textit{effective stress} \leq \textit{allowable stress}$$

The allowable stress usually is defined as

$$\textit{allowable stress} = \frac{\textit{material characteristic}}{\textit{safety factor}}$$

The static strength analysis is a typical example in this case with using either the yield strength or the tensile strength (for steels) as "material characteristics" depending on the material behaviour.

The selection of the safety factor varies depending on the failure consequences and on the applied material characteristics. If for example the design of a component of ductile material is made against plastic deformation (Yield strength-value), a small safety factor may be selected because inherent not quantified margins against rupture are still available. It is important to chose correspondingly higher safety factors if rupture is considered based on the Ultimate tensile strength R_m (UTS). The consideration of both the yield strength and the tensile strength is often used when defining the allowable stress, for example, in defining the S_m value in the nuclear codes.

The gist of this procedure provides the basis for all design instructions and codes. Besides explicitly required safety factors additional inherent safety margins are available by a defined minimum value (acceptance criteria) to be used as material characteristics. A statistical analysis based on an evaluation of a large number of representative test results usually defines these acceptance criteria. Frequently, the "average values minus double of standard deviation (-2s)" are taken as measure for the acceptance criteria.

The fracture mechanics characteristics are treated in the codes – if at all - in a different way. The state of the art is demonstrated in the following together with a recommendation to unify the procedure.

2 Consideration of fracture mechanics parameters in the safety analysis

In the field of fracture mechanics various parameters are used depending on the deformation behaviour of the materials and consequently depending on the failure behaviour.

The application of each fracture mechanics evaluation method requires that first a decision is made against which failure mechanism this evaluation has to be carried out. In a simple case, this would be an assessment of the fracture loading, generally also considered as "instability" of the components cross section .

In a more sophisticated analysis also mechanisms and failure stages preceeding the final fracture should be analysed. This is in analogy to the tensile test, where not only the ultimate strength, but also yield strength and the whole stress strain curve are measured. In the fracture mechanics test such preceeding mechanisms are the loading at crack initiation as well as the crack growth prior to failure. The crack initiation parameter [1] proved to be a transferable material-specific parameter. On the other hand the crack growth processes and the subsequent instability point are subjected to external influences such as specimen size, crack geometry, type of test performance, multi-axiality of the stress state, and so on [2].

In ferritic steels the deformation behaviour and so the fracture behaviour distinctly change depending on the temperature.

A high degree of energy dissipation capability in form of stable crack propagation prior to instability (if it occurs at all) after exceeding the crack initiation parameter is assured in the upper shelf of the toughness depending on the toughness level. In other words: The instability value is much greater than the initiation value.

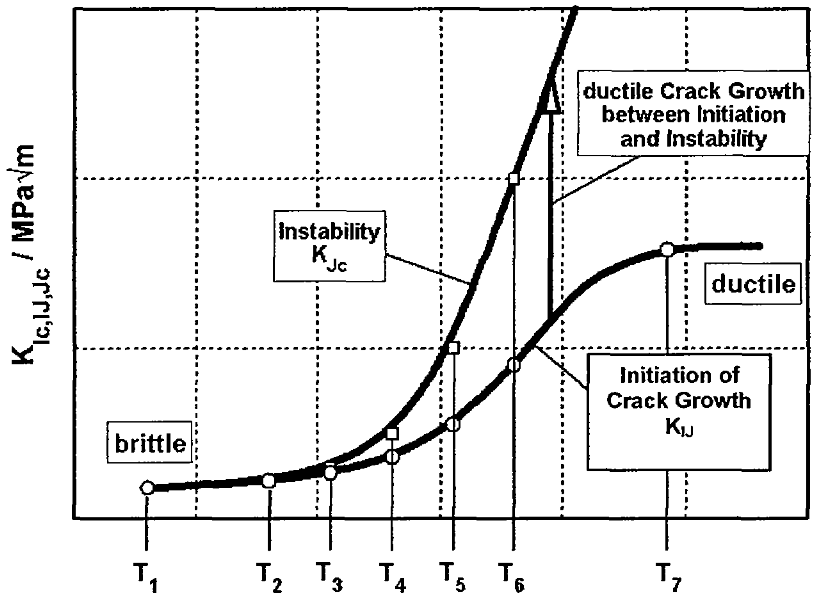


Fig. 1: Temperature dependence of the initiation and instability values

At lower test temperatures one can see that the energy dissipation capability and thus the initiation value and also the subsequent stable crack growth prior to reaching the instability reduces. This means that there is less difference between the initiation and instability value. In the limiting case of very deep temperatures the ductility of the material is constricted in such a way that stable crack growth is nearly zero and instability occurres immediately after the initiation [3] of the crack growth process, see fig. 1. One can obtain the same behaviour independent of the temperature if the multi-axiality of the stress state is very high.

It is possible to conclude from this issue that safety factors in various magnitudes shall be used in safety analyses depending on the available fracture-mechanics material characteristics. If the evaluation is made against instability, the choice of the safety factor has to be greater than in the case of initiation.

3 Evaluation of fracture-mechanics characteristics according to the code

Initially, the fracture mechanics characteristics to evaluate components in codes was implemented for the first time in the American nuclear code to safeguard against brittle fracture using the K_{Ic}-value to characterise the brittle initiation, [4]. An enveloping limit curve was empirically defined from the then known K_{Ic}values of typical materials. Safety factors were demanded depending on the loading case considered either indirectly (via conservative calculation of the effective load) or directly.

This procedure retains nearly unchanged up to now in nuclear Codes, e.g. KTA [5] even if few (substantiated) data are not completely enveloped. The shape of the limit curve is constant and its position over the temperature is defined material-specifically by the "reference temperature" RT_{NDT}, fig. 2.

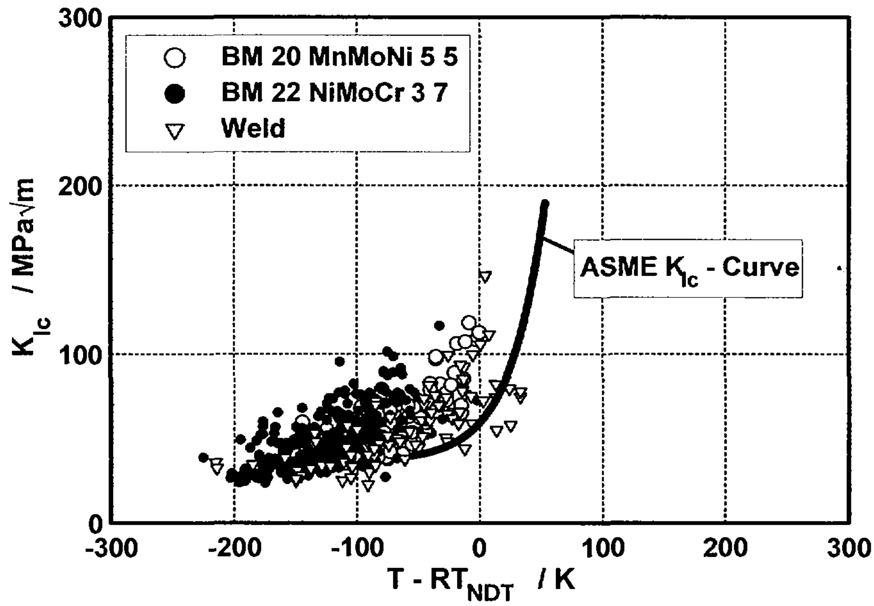


Fig. 2: **K_{Ic} –curve in comparison to MPA data for K_{Ic}-values**

The latest development in the field of nuclear codes are giving way to allow an assessment curve resulting from statistical considerations instead of the empirically defined limit curve used up to now, e.g. [6]. The essential difference in the procedure up to now is the fact that the "old" reference temperature RT_{NDT} will be replaced by a "new" reference temperature RT_{T0}. This temperature is based on the Transition Temperature T_0 which is determined by a statistical evaluation from fracture-mechanics characteristics (cleavage instability K_{Jc}) in accordance with the procedure [7, 8] known as "Master Curve" (MC). The assessment curve with a shape which corresponds to that of the earlier enveloping limit curve (K_{Ic}-curve) is adjusted according to [6] in the new reference temperature $RT_{T0} = T_0 + 19.4$ K.

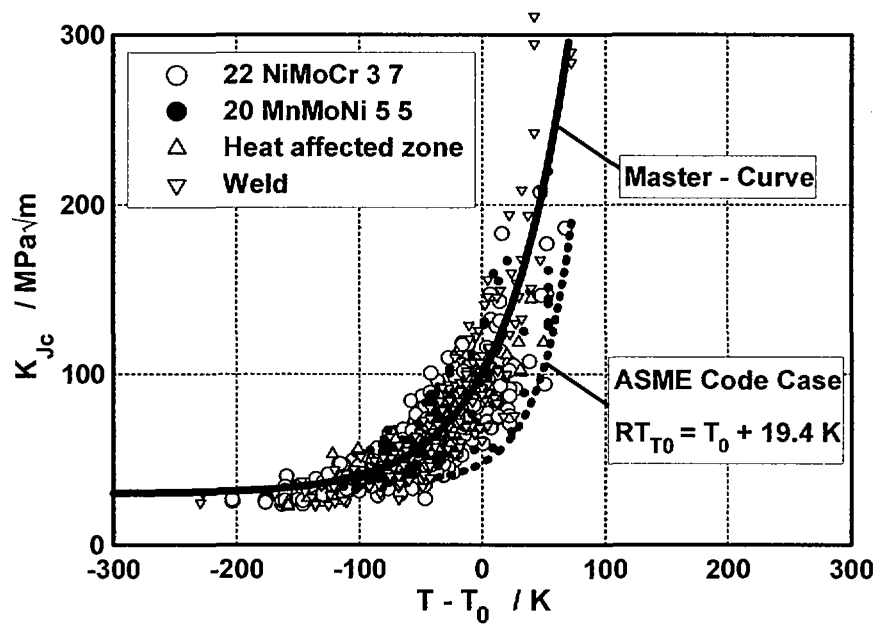


Fig. 3: **K_{Jc}-based Master Curve and limit curve according to ASME Code Case**

Contrary to the determination of the reference temperature RT_{NDT} in determining the Transition temperature T_0 fracture values for instability K_{Jc} are used which may be considerably above the crack initiation value K_{IJ} because of considerable plastification and noticeable crack growth prior to cleavage instability. This is a very important fact in view of safety factors to be additionally applied.

Besides the nuclear codes fracture mechanics evaluation procedures and related material characteristics have also been implemented in conventional codes in the latest developments.

The so-called Eurocode III (EC 3) used for the design of steel structures can be taken as an example [9].

In this code the procedure according to Master Curve was also chosen as a basis for the components assessments. This means that instability values are considered. In order to simplify applications in the Eurocode III the Transition temperature T_0 was replaced by the temperature T_{28J} which can easily be determined by the Charpy-V-notch test. The correlation used is called $T_0 = T_{28J} - 18$ K, [10]. This is good for practical applications because the material behaviour can also be quantified by fracture mechanics parameters without running extensive and expensive fracture mechanics tests. On the other hand, it is important for the discussion about using safety factors that the Transition temperature T_0 has been determined from instability values. Additional inaccuracies may be caused by the uncertainties in the correlation between T_0 and T_{28J}.

A comparable procedure to define the fracture mechanics parameters is used in the European analysis procedure "SINTAP" [11]. This procedure includes a fracture toughness curve for the total relevant temperature range put together from two ranges. In the lower shelf and transition area the mean curve (50%) of the Master Curve concept (instability) is indicated. It is adjusted to the Transition temperature T_{28J} similar to EC3. The correlation between T_{28J} and T_0 here is called $T_0 = T_{28J} + 3$ K. A horizontal straight line is defined in the upper shelf area as a function of the upper shelf notch impact energy of the material. It has been derived from a correlation between the "technical crack initiation characteristics $J_{0,2}$" [12], Fig. 4 and the upper shelf notch impact energy. This also is of great advantage to the application meaning that only results from the notch impact bending test have to be known to guess the fracture-mechanics properties. Finally this also means that the fracture-mechanics "materials curve" in the lower shelf and transition area is based on instability values and in the upper shelf area on "initiation values".

This fact in combination with the use of correlations with their individual scattering requires careful consideration in defining the safety factors. SINTAP allows for the area lower shelf and transition range the use of fracture toughness curves given in the MC-procedure representing distinct probabilities of failure. However, no recommendation is given for a certain probability of failure to be used. In the upper shelf an envelop curve can be used if there are little data. If sufficient data is available for an individual statistical analysis the use of the –1s-curve or a 20 % probability curve is recommended.

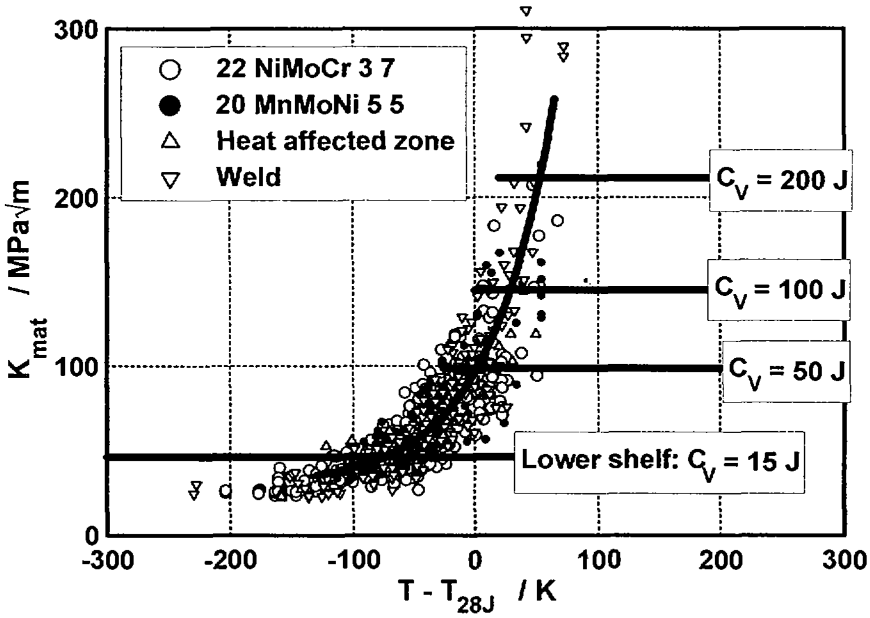


Fig. 4: Evaluation according to SINTAP

4 Proposal of MPA Stuttgart to determine a fracture toughness temperature curve in the total relevant temperature range

A proposal of MPA Stuttgart for the determination of a closed fracture toughness curve in the total relevant temperature range proposes a "multi-step procedure". The whole concept is based on the assessment of initiation of crack growth, not on the assessment of instability. Depending on the available material characteristics, in different steps of the procedure each an assessment curve can be obtained which includes safety factors depending on the accuracy and the physical meaning of the material characteristics.

The most extensive and expensive but also mostly used approach (step 1) is the experimental determination of the initiation values in the fracture mechanics tests both in the transition range as well as in the upper shelf. For this purpose small fracture mechanics laboratory specimens can be used because the initiation values are independent of specimen size and geometries [1, 2].

At least six fracture mechanics specimens are tested according to this approach in the transition range of the toughness. The J_i values determined using the stretch-zone-method (cf. [1, 12, 13]) are converted formally in K_{iJ}-values (EDZ). Additional crack length corrections are not used as for the MC-method. An approximate use of a MC curve adjustment will determine the temperature with a K_{iJ}-value of 100 MPa√m. This temperature is termed as $T_{K100Init}$. This transition temperature is used to adjust an assessment curve which has been determined from a large number of tests on different materials, as shown in the following.

If data from various materials are adjusted on their individual transition temperature $T_{K100init}$ they can be analysed together as one large data set using a Gauß distribution of the initiation values. The result will be the mean value curve and curves for standard deviations. Fig. 5 illustrates the result of such an approach for a number of melts / heats of the pressure vessel materials 22 NiMoCr 37 and 20 MnMoNi 55 with their welded joints (WM and HAZ) both for the unirradiated and irradiated material state. This data shows that one can refer to the –2s-curve for defining the "assessment curve".

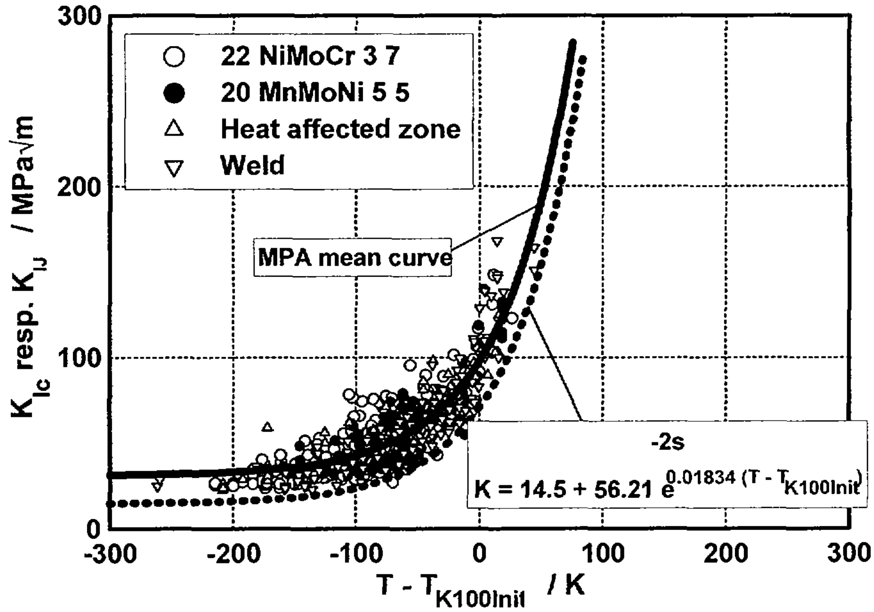


Fig. 5: Statistical evaluation of initiation values in the lower shelf and transition

This curve intended for safeguarding the initiation in the lower shelf and transition range can be extended into the upper shelf using a statistical analysis of experimental results of a large number of steels. Fig. 6 shows the correlation of initiation values J_i with the mean value of the notched bar impact energy CV. Also in this case a statistic analysis results in a curve of the initiation value J_i at –2s as function of the notched bar impact energy.

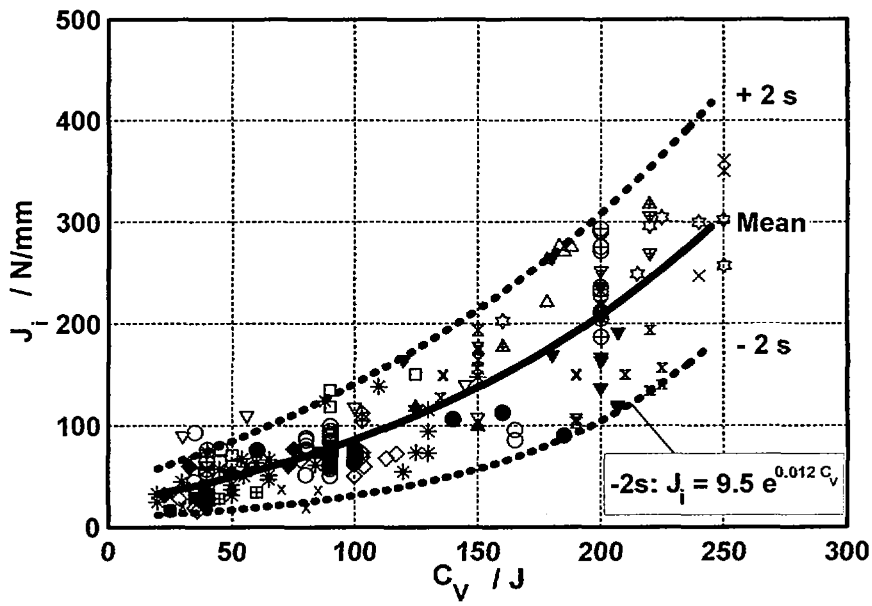


Fig. 6: Statistical evaluation of initiation values in the upper shelf

If these results are used for defining an assessment curve (fracture toughness temperature curve for the total relevant temperature range including safety factors) the outcome is demonstrated in Fig. 7. In practice this means that a complete fracture toughness-temperature curve for a material state to be analysed can be provided by tests on six fracture mechanics specimens and form the notch impact energy value in the upper shelf. This curve can completely be taken as reference for evaluating components because of its statistical safeguard (-2s-curve) and the inherent safety (initiation consideration with margin against instability, direct transferable characteristics. Additional safety factors can, if necessary, be kept small. A disadvantage of this method against the MC-procedure is the more extensive and expensive determination of the J_i values.

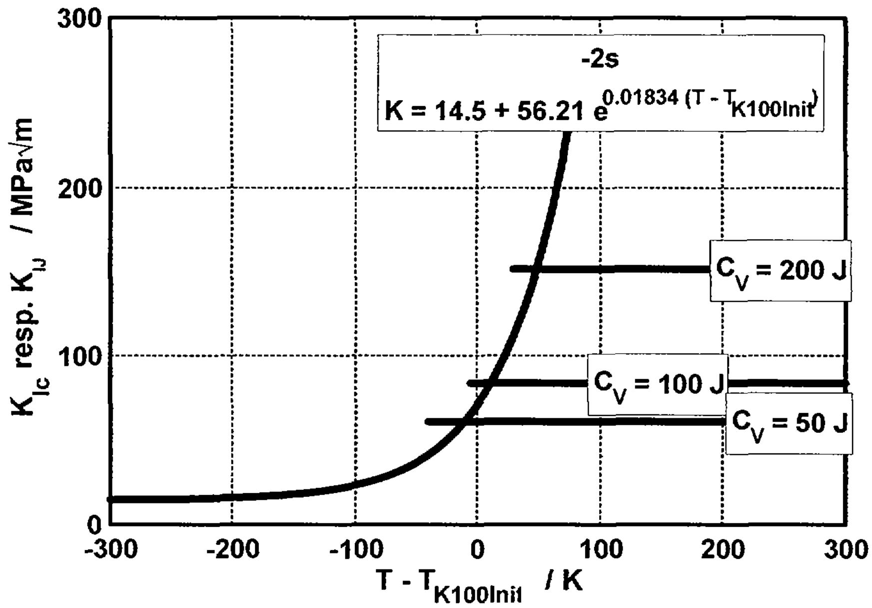
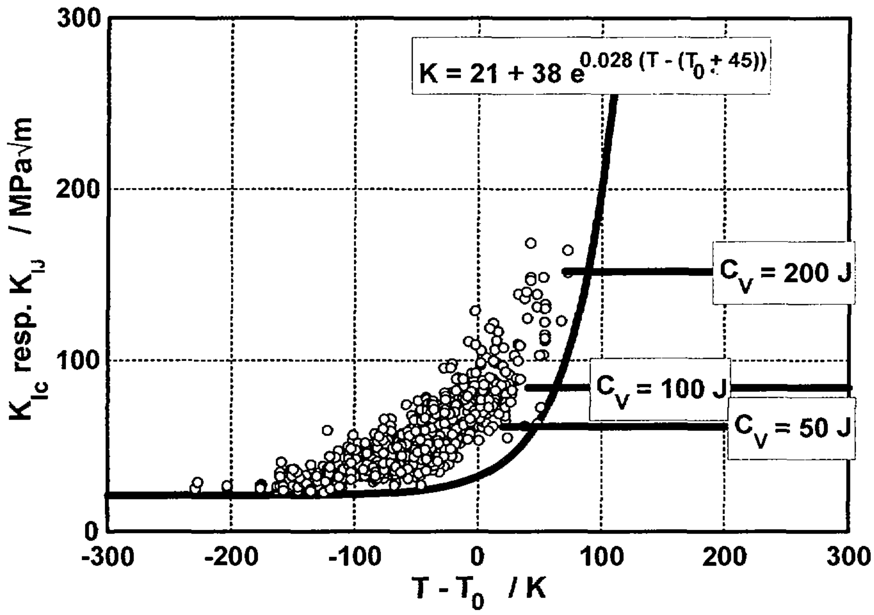


Fig. 7: Statistically proven evaluation curves for crack initiation, adjusted to $T_{K100init}$

If for any reasons no initiation values J_i shall be determined, the assessment curve can also be defined using instability values K_{Jc} following the original MC approach to determine the T_0 value (Step 2 of the MPA evaluation concept). The determination of T_0 according to MC also – as in the case of $T_{K100init}$-determination - requires testing of at least 6 fracture mechanics specimens. However, the test performance and evaluation is less extensive and expensive because of not determining the initiation.

Fig. 8 shows the complete data set of fig. 5 with the initiation value K_{IJ} referring to the MC Transition temperature T_0 of the appertaining K_{Jc}-instability values. This deviates from fig. 5. An assessment curve from this data has the advantage of describing on the one hand, initiation values and, on the other hand, starts from the simple to be determined Transition temperatures T_0 according to MC. On the basis of this approach it is possible to define an "envelop curve" with this data. It meets completely the known data of initiation values. The curve shape determined corresponds largely to the known K_{Ic}-limit curve (with reference to the shape in the increasing transition area). Furthermore, the fracture toughness level at the reference temperature is at 59 MPa√m according to the KTA /

ASME K_{Ic}-curve allowing a direct quantitative comparison with the reference temperature RT_{NDT}. The resulting procedure by defining the reference temperature as RT = T_0 + 45 K is very similar to the procedure of the ASME Code Case N-629 [6], however the ASME Code cases (RT_{T0} = T_0 + 19.4 K) covers instability where the proposed MPA curve covers initiation.



<u>Fig. 8</u>: evaluation curves for crack initiation, adjusted to T_0

An additional modification and simplification can be obtained (Step 3 of the evaluation concept), if instead of the experimentally determined T_0 using fracture mechanics specimen the correlation between T_{28J} and T_0 is to be employed as e.g. in EC3 and SINTAP. In contrary to SINTAP, where a mean value (50%) consideration of instability values K_{Jc} (transition) and technical crack initiation values $J_{0.2}$ is done, here a statistically based curve is available with the character of safeguarded crack initiation values. Because of its modified approach to this curve it is to be evaluated with an increased safety factor as against Fig. 8. However, it represents a sufficient approximation for many practical applications.

5 Example of Application

In the public literature it is simple to find large data sets for instability values which allow to compare instability based procedures to large data sets. However, due to a very limited availability of consistent data sets of initiation values it is difficult to compare the initiation based approaches to many available experimental data. A large data base of initiation values thus has been produced in a recent research project performed at MPA Stuttgart, [14].

In this research project various fracture mechanics specimens with different shape, size and crack configurations have been taken from a segment of an original PWR-RPV , produced in original technology (material 22 NiMoCr 3-7 including all steps of the RPV manufacturing including cladding process and heat treatment processes, wall thickness 250 mm).

Fig. 9 shows the initiation values K_{IJ} of the investigated fracture mechanics specimens versus temperature. A continuous course from lower shelf to transition and upper shelf level can be seen.

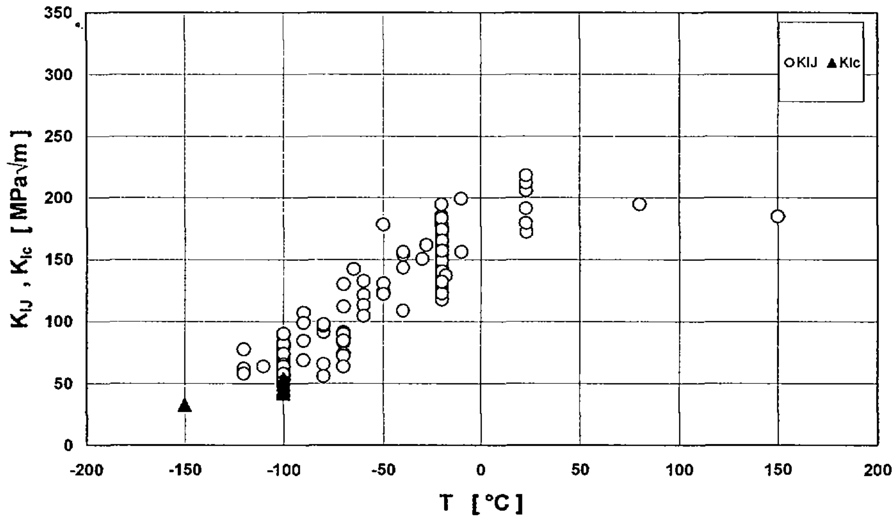


Fig. 9: 22 NiMoCr 3-7, K_{IJ}-values from [14]

The comparison of the initiation values with the assessment curve according to step 1 ($T_{K100init}$ – based –2s curve) of the MPA assessment procedure is shown in fig. 10 demonstrating the accuracy of this method in the whole temperature range. All initiation values are covered by this assessment method without too large conservatism.

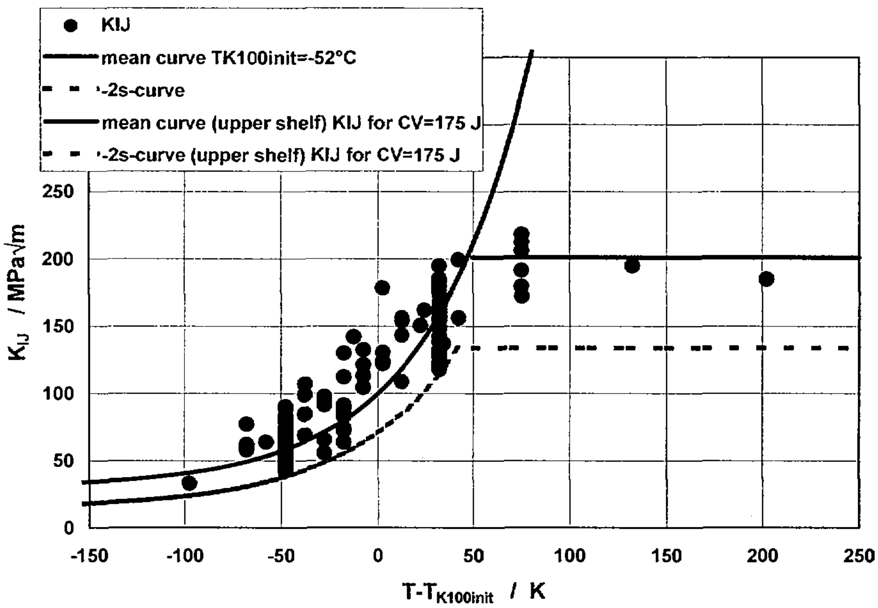


Fig. 10: Initiation assessment curves based on $T_{K100init}$ and CV (upper shelf) in comparison to experimental K_{IJ}-values

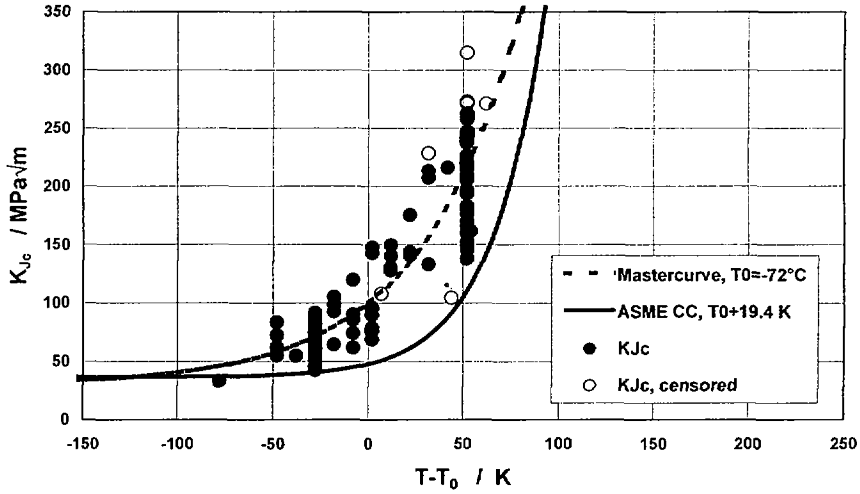


Fig. 11: Application of ASME Code Case [6] to the instability data K_{Jc} from [14]

Fig. 11 shows the application of the ASME Code Case [6] procedure to the instability data as produced in [14]. As expected the instability values K_{Jc} as per ASTM E1921 [8] are above the curve adjusted at the reference temperature RT_{T0} = T_0 + 19.4 K and demonstrate the feasibility of the ASME Code Case [6] procedure to cover instability values in this case.

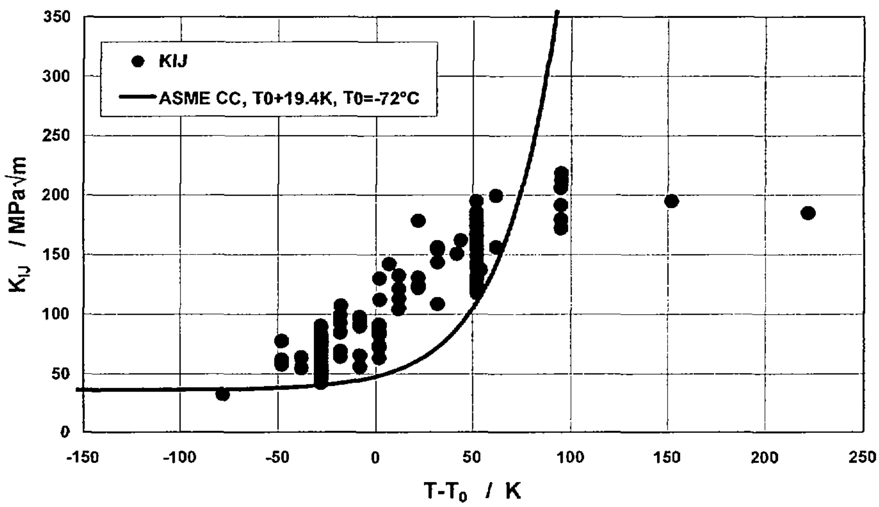


Fig. 12: Comparison of ASME Code Case curve [6] with initiation data from [14]

Fig. 12 shows a comparison of the ASME Code case curve , adjusted at RT_{T0} = T_0+19.4K (which has been considered up to now in combination with instability values K_{Jc}) with initiation values K_{IJ}. It can be seen from this figure that this curve , adjusted at T_0 (instability based) + 19.4 K in this case even envelopes the initiation values. However, this holds for the actual data base but can not be generalized according to other data sets of MPA.

As mentioned the basis of the MPA approach is to assess the initiation values K_{IJ}, also in step 2 of the procedure. If this has to be done using instability based T_0 values in cases, when only the instability based T_0-values are available, the assessment curve has to be adjusted at a temperature RT = T_0 + 45 K according to previous MPA results. The application of this procedure to the new data set generated in [14] is shown in fig. 13. It can be seen from this result that this procedure is verified as conservative also with this new data set. It turns out very clearly the determination of initiation values K_{IJ} should be the preferred way in order to reduce too high conservatisms which may be consequence of focusing only on the cleavage instability values K_{Jc}.

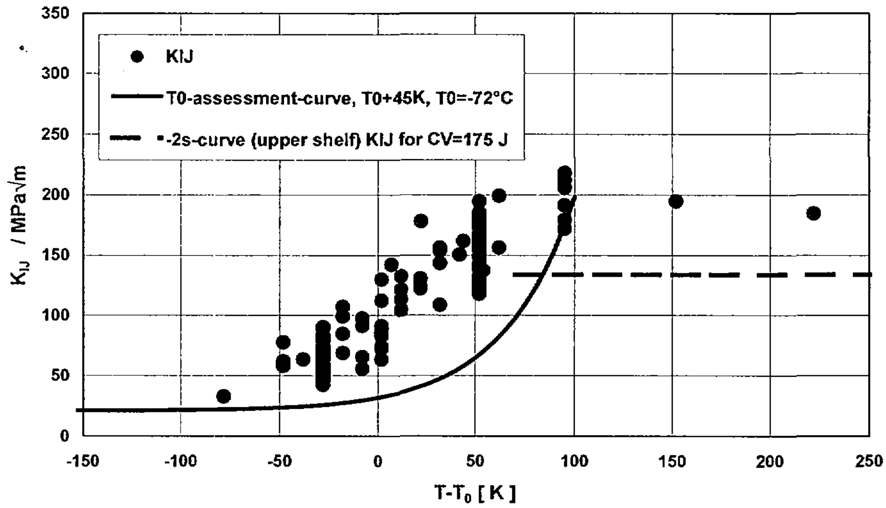


Fig.13: Comparison of the instability based assessment curve (step 2 of MPA procedure) with initiation values K_{IJ}

6 Summary

Statistical evaluations of existing data for fracture mechanics characteristics make it possible to prove assessment parameters as a basis for safety related component assessments. Various modified assessment methods were discussed against the background of the required safety margins. It could be shown that in defining the safety margins to be used in the calculation as an essential parameter it has to be checked whether the component evaluation safeguards crack initiation or component instability. A proposal was made to standardise the derivation of fracture mechanics initiation values over the whole temperature range of fracture toughness from lower shelf up to the fracture toughness upper shelf.

7 Literature

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