SCATTER OF A FERRITIC STEEL IN THE TRANSITION REGION ANALYSED BY CHARPY TESTS AND DYNAMIC TENSILE TESTS

W. Böhme*, G. Bernauer*, W. Schmitt*

Several series of static and dynamic experiments with a German reactor pressure vessel steel have been performed at different temperatures. Besides results of standardized compact tension tests and static and dynamic tensile tests, results of instrumented Charpy-V tests and of dynamically loaded notched round bars are presented. In addition to the evaluation of *J*-values these tests were analysed numerically by means of a micromechanical damage model in order to finally determine the Weibull parameters of the Beremin model. However, not all of the results of the different series of tests are consistent, suggesting the need for modifications of the evaluation or the model to enable the application to arbitrary temperatures and loading conditions.

INTRODUCTION

Following the concept of Beremin (1) it is possible to determine cleavage fracture stresses and the corresponding Weibull parameters σ_u and m from of a series of notched bar tensile tests. Based on the assumption that these quantities are independent of strain rate and temperature it should be possible to predict the variation of cleavage toughness with temperature or strain rate, if the dependence of the stress-strain curve on strain rate and temperature is known.

This contribution focuses on the influence of both temperature and strain rate. Therefore, especially results obtained at high loading rates are presented and discussed. More detailed information is given by Böhme et al (2).

DYNAMIC TENSILE TESTS

The material under investigation is a ferritic reactor pressure vessel steel, German designation 22 NiMoCr 3 7, with a lower yield point of 492 MPa at room temper-

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* Fraunhofer-Institut für Werkstoffmechanik (IWM)
D -79108 Freiburg, Wöhlerstrasse 11

ature, a Charpy upper-shelf energy of about 200 J, and a transition temperature of $T_{\ddot{u},41J} = -46$ °C.

Dynamic tensile tests have been performed at different temperatures with smooth tensile bars (diameter 6 mm, gauge length 30 mm) in a drop weight tower with an impacting mass of 273 kg and an impact velocity of 2 m/s, yielding an initial strain rate $\dot{\varepsilon} \approx 50/\mathrm{s}$. For the evaluation of true stress vs. true strain curves the area reduction and the necking radius of the specimens were measured from photographs taken with a 24-spark Cranz-Schardin high speed camera (Böhme et al (3)). The true stress vs. true strain data determined from the dynamic tests are corrected according to Bridgman and are presented for two temperatures in Fig. 1 in comparison with static results. At small strains the dynamic stresses are significantly higher than the static ones. With increasing strains the high rate data approach the static results. This behaviour is caused by adiabatic heating in the necking region (3) which results in an apparent softening of the material.

NOTCHED ROUND BAR EXPERIMENTS AND CHARPY-V TESTS

To characterize the cleavage fracture behaviour of the material dynamic experiments with notched round bars (R-Bar(T)) using the same experimental set-up as described above and instrumented Charpy-V tests were conducted. Fig. 2 shows the excellent reproducibility in force vs. time traces of ten Charpy-V tests at -10 °C. The onset of cleavage (i.e., the abrupt load drops) at different times indicates the scatter of the cleavage stresses. All experiments showed ductile crack extension prior to cleavage fracture.

The Charpy-V tests were evaluated in terms of a "cleavage R-curve" by integrating the corresponding force-displacement curve up to initiation, yielding the partial energy W_{iu}. Consequently J-values were calculated by applying the equation $J_u = 1.46\, W_{iu} / \{B\, (W-a_o)\}$ for the relative notch depth of $a_o/W = 0.2$ according to Helms et al (4). The resulting crack-resistance data are given in Fig. 3. It was demonstrated by Böhme (5), that this so called "cleavage R-curve" seems to form a lower bound in comparison to results of low-blow tests or key-curve methods. However, because of not satisfied size requirements (due to the high toughness of the material and the limited size of the specimens) these values are not directly transferable to structures, but can be used for an improved, comparative characterisation of ferritic steels.

In addition to the Charpy-V data also results of statically and dynamically loaded notched round bars are given in Fig. 3. For an easy evaluation a simple equation relating the elongation ΔL with J was established from results of numerical calculations (2): $J_u = 1350\ \{\mathrm{MN/m^2}\}\ \Delta L_u$. The possible systematic error of this equation is estimated to be less than ± 50 kN/m up to elongations of 1 mm.

The J_u-data of the tests at the two lowest temperatures yield results left of the blunting line, which was calculated in a formal manner for the range of temperatures and strain rates of the other tests. The latter yield results, which seem to form a unique crack resistance curve. At a first glance, this is contradictory regarding current knowledge about constraint effects (see e.g. Brocks and Schmitt (6)), because one would expect steeper curves for tension (R-Bar(T)) than under bending (Charpy-V). Different slopes of J_R-curves due to constraint effects are expected, if the data are clearly on the right hand side of the 0.2 mm offset line. Here, however, the material behaves so tough, that all comparable data sets are within this 0.2 mm limit up to very high J-levels and, therefore, the situation is different.

ANALYSES OF THE SCATTER IN THE TRANSITION REGION

A purely experimental quantification of the scatter can be done based on the J_u-values. A Weibull diagram of these data is presented in Fig. 4. There is a broad variation regarding the mean values of the different series and the slopes are different, too. This is of course due to the fact, that there is a transition from the lower shelf to the upper shelf relating to the low and high values of J_u, respectively.

In order to evaluate the Weibull parameters of the Beremin model two-dimensional (R-Bar(T)) and three-dimensional (Charpy-V) finite element simulations of the tests were performed based on a modified Gurson model (Needleman and Tvergaard (7)). The ductile crack extension prior to cleavage fracture was taken into account and a temperature and strain rate dependent deformation model was applied (see (3) and Bernauer (8, 9)). A Weibull diagram of the numerically calculated critical stresses σ_w at the onset of cleavage fracture is given in Fig. 5. If all possible influences are correctly taken into account by the analyses and the Beremin model then all results should form a unique curve, to qualify the Weibull parameters as material parameters. Fig. 5 includes also results of static tests with notched bars and compact specimens. The results of the comparable dynamic R-Bar(T) and Charpy-V tests at the same temperature of -50 °C are close together, despite of the different loading conditions (tension and bending). Also the static experiments with notched tensile bars at the two lowest temperatures yield similar results regarding the slope and the level of the Weibull stresses. But there are also series of tests with significantly different results which, therefore, suggest the need for modifications of the evaluations or the Beremin model to enable a reasonable application to arbitrary temperatures and loading conditions.

CONCLUSIONS

To investigate the influence of temperature and strain rate on the behaviour of a ferritic steel in the transition region several series of tests have been carried out and analyses based on fracture mechanics evaluations and on the local approach of Beremin have been performed. For the need of numerical calculations static and dynamic true stress vs. true strain curves were determined. A comparison showed significant differences reflecting effects of strain rate and adiabatic heating in the necking region of the specimens.

To characterize the cleavage fracture behaviour of the material dynamic experiments with notched round bars and instrumented Charpy-V tests were performed. Within each series of tests all specimens experience the same deformation history until the onset of cleavage fracture, the scatter of which was analysed. J_u-evaluations of this onset of cleavage fracture result in crack resistance data. All data obtained around -50 °C including results of C(T) tests seem to follow a unique "cleavage R-curve". This might be due to the high toughness of the steel under investigation.

To apply the Beremin concept for cleavage fracture all tests were analysed numerically with a strain rate dependent, modified Gurson model. The observations suggest the need for modifications of the evaluations or the Beremin model to guarantee transferability from specimens to structures over a wide range of loading conditions and geometries.

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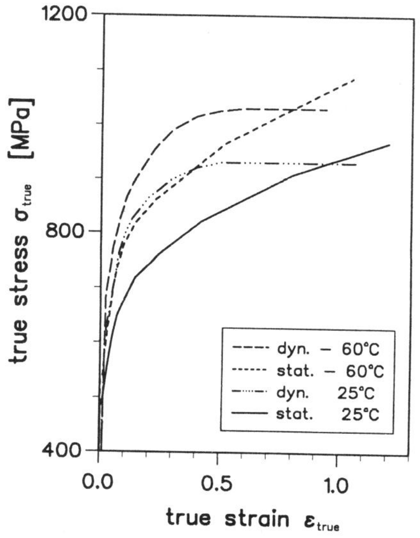

Figure 1 True stress vs. true strain curves from static and dynamic tests

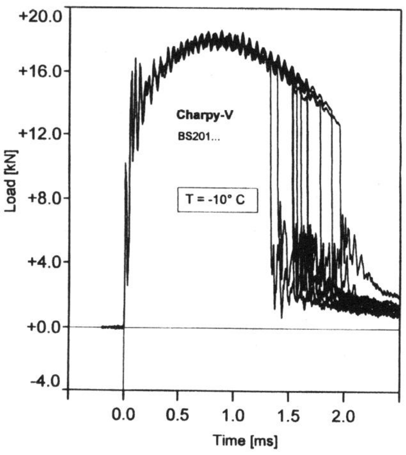

Figure 2 Force vs. time traces of ten Charpy-V tests at -10 °C

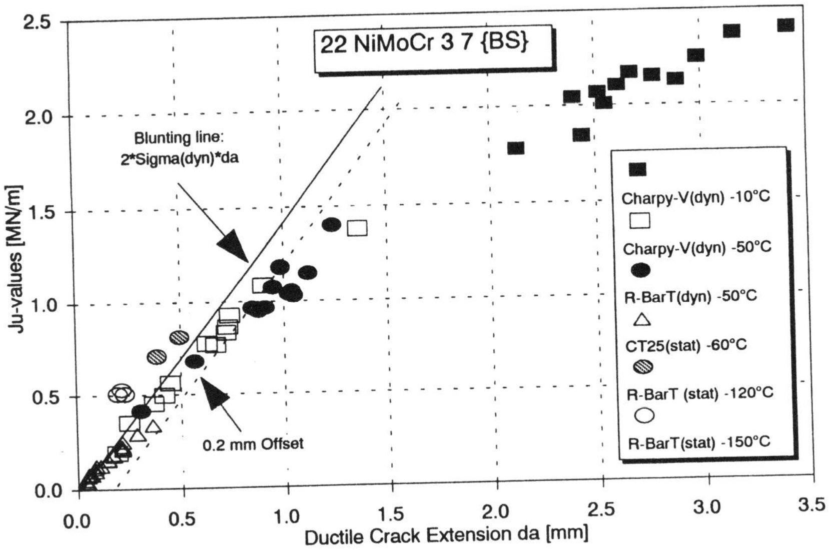

Figure 3 Crack resistance data for different test conditions

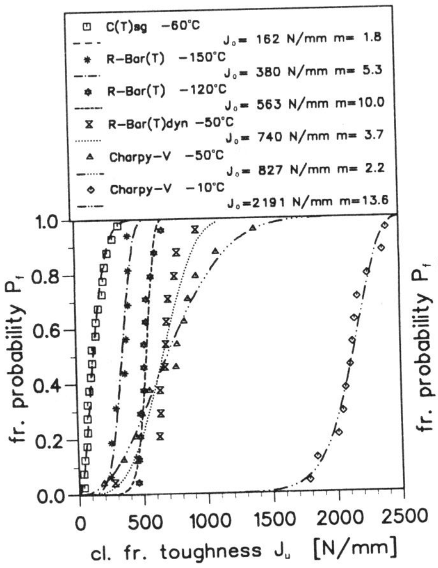

Figure 4 Weibull diagram of the J_u-values of all tests

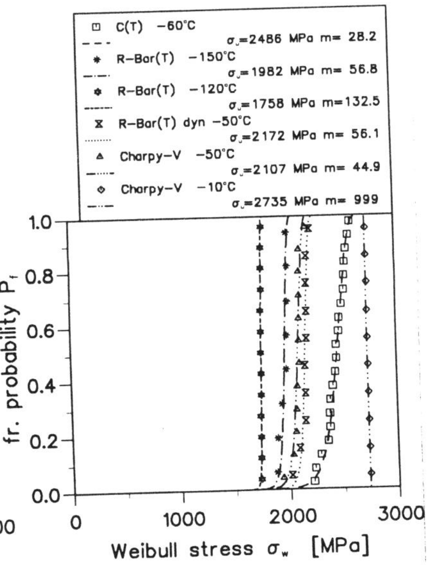

Figure 5 Weibull diagram of the σ_w-values (Beremin) of all tests