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THE INFLUENCE OF LOADING RATE ON $J_R$-CURLVE OF 20 MnMoNi 5 5 STEEL USING THE KEY CURVE METHOD

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Résumé
On a établi les courbes $J_R$ d'un acier 20 MnMoNi 5 5 à diverses vitesses de chargement par la méthode de la courbe de référence. Pour cela on a établi la courbe de référence par calculs aux éléments finis en tenant compte de l'effet de vitesse de déformation sur le comportement plastique. On met en évidence la croissance des valeurs $J_R$ avec la vitesse de chargement.

Abstract
$J_R$-curves of 20 MnMoNi 5 5 steel at different loading rates were determined using the key curve method. For this the key curve function was developed by FE-calculations in consideration of the yielding behaviour depending on strain rate. The evaluated $J_R$-curves increased with higher loading rates.

1. Introduction

In many cases it is essential for the prediction of failure to know the material behaviour under loading conditions as they occur in components or structures. Not only yielding and work hardening behaviour but also the fracture behaviour characterized by the $J_R$-curve in the ductile temperature region has to be determined as a function of temperature and loading rate. The experimental procedure for dynamic $J_R$-curve testing involves problems due to crack length measurement. Usual methods like unloading compliance, potential drop technique, ultrasonics and multi-specimen-technique are not suitable for dynamic testing. Thus the key curve method developed by Ernst et al. /1/ appears to be a promising alternative for $J_R$-curve determination, because the crack extension can be obtained directly from the load displacement record if a key curve function is available.

2. Description of the key curve method developed by Ernst /1/

Basically unloading compliance and key curve method are similiar. In the first case the crack extension is derived from the elastic compliance whereas in the second case crack extension is obtained from a calibration or key curve function, which represents elastic and plastic specimen behaviour. This calibration function depends on yielding and work hardening behaviour of the material and consequently on strain rate and temperature. Fig. 1 proves that load displacement curves of geometrically similar CT-specimens with constant $a/W$-ratio are identical, if the load $F$ and the displacement $A$ are divided by the proper specimen dimensions. The normalized load value

$$F_1 = \frac{F \cdot W}{B \cdot b^2}$$

$W = \text{specimen width}$

$B = \text{specimen thickness}$

$b = \text{ligament length}$
in the diagram is the tensile stress $F/(W \cdot B)$ divided by the ratio $(b/W)^2$ which implies the dependance of bending stiffness on ligament size. According to Joyce /2/ $F_1$ becomes therefore independent of $a/W$ for 3-point-bend specimens and the key curve function is given by $F_1 (\Delta/W)$. In contrary, for CT-specimens the normalized load displacement curve $F_1(\Delta/W)$ additionally depends on the $a/W$-ratio so that the key curve function is given by the function $F_1 (\Delta/W, a/W)$. Ernst has developed the "key curve" experimentally using subsized specimens, because they can be loaded until higher values of $F_1$ and $\Delta/W$ without stable crack growth. The experiment for $J$-curve determination has then to be carried out with a larger geometrically similar specimen where crack initiation occurs at lower values of $\Delta/W$. Fig. 2 presents the load displacement record of a ICT-test-specimen with $a/W = 0.65$ and load displacement curves for 3 $a/W$-ratios for the same specimen size derived with the calibration function. The point of deviation indicates crack initiation and at the points of intersection the instantaneous crack length of the ICT-specimen is given by the $a/W$-ratio of the respective load displacement curve. This procedure supposes that the applied load of a specimen at a given combination of $\Delta/W$ and $a/W$ is independent of the path in a $\Delta/W$-$a/W$-field. The expressions for the calculation of crack extension $\Delta a$ and $J$-integral are given in /1/.

Fig. 1: a) Load displacement curves of CT-specimens, b) Normalized load displacement curve

Fig. 2: Comparison of load-displacement curves to determining stable crack growth
3. Application of the key curve method to $J_R$-curve determination at high loading rates

In the present work the key curve function was developed by FE-calculations because the experimentally determined one has three principle disadvantages:

1. The scatter of load displacement behaviour causes an uncertain $\Delta a$ determination especially in the region of crack initiation.

2. Using subsized specimens only a limited region of the key curve function can be obtained as it shows Fig. 3. At a supposed $J_{IC}$-value of 150 N/mm the crack initiation loads of different geometrically similar CT-specimens (left diagram) can be transferred in the related load-displacement curve (right diagram). It appears that due the above supposed $J_{IC}$-value a calibration function can only be determined with $1/2$ CT-specimens until $\Delta/W = 0.035$ because crack growth takes place afterwards.

![Fig. 3: Signification of CT specimen size for the load displacement point of the initiation of stable crack growth](image)

3. The experimental procedure is very expensive because of the great number of subsized test specimens.

**FE-calculations**

FE-calculations were carried out to determine load displacement curves for CT-specimens with $a/W$-ratios between 0.5 and 0.75 (6 specimens) under plane strain conditions. The elastic-plastic calculations were performed by the FE-program ABAQUS using the von Mises yield condition and isotropic strain hardening. The uniaxial stress-strain curve was represented by a multilinear approach. A geometrical nonlinear formulation was used.

**Experimental procedure**

Fracture mechanics tests were performed with 20 % side grooved 1CT-specimens at constant displacement rates between 0.01 and 570 mm/s. The CT-specimens were loaded up to certain displacement values. The investigated material was a quenched and tempered 20 MnMoNi 55 steel. Table 1 presents chemical composition and heat treatment of the steel. As yielding and work hardening behaviour of steel depends on strain rate $\dot{\varepsilon}$, key curve functions corresponding to the displacement rates had to be determined. Yielding behaviour was investigated as a function of strain rate. For two stress-strain-
Curves at different strain rates FE-calculations were carried out to develop a calibration function.

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<th>S</th>
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<td>.16</td>
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<td>.48</td>
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</tr>
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</table>

Quenched and tempered: 900°C/40 min/oil/650°C/80 min/air

Table 1: Chemical composition and heat treatment of 20 MnMoNi 55 steel

Fig. 4: a) True stress strain curve for two different strain rates at room temperature, b) Key curve normalized with yield behaviour

Fig. 4 shows stress strain curves and FE-calculations. The calculated load displacement curves are nearly identical if F1 is related to the lower yield point and Δ/W to the elastic strain at the lower yield point ε0. Therefore it appears to be more sensible to make only one FE-calculation by converting a related calibration function to the appropriate yield strength with respect to the strain rate, instead of performing FE-calculations for each strain rate. Fig. 5 presents the lower yield strength as a function of the activation energy AG. According to Krabiell et al. /3/ the lower yield strength can be calculated for any required strain rate on the basis of thermally activated yielding. The strain rate near the crack tip was evaluated according to Shoemaker /4/ at the moment of general yield:
Time and place dependance on strain rate had been neglected and the estimated strain rate was regarded to be characteristic for the specimen behaviour.

\[
\frac{\sigma}{E \cdot t_0} = \frac{2 \cdot \sqrt{3}}{R_{\text{el}}}
\]

**Fig. 5:** Yield stress \(R_{\text{el}}\) as a function of activation energy

Results and conclusions

In order to verify the methodology total stable crack extensions where measured after the specimens had been heat tinted and broken at liquid nitrogen temperature. Fig. 6 shows the good agreement between measured and from equation 3 calculated crack extensions. The evaluated \(J\)-curves of different loading rates in terms of \(dJ/dt\) are presented in Fig. 7. With the exception of the \(J\)-curve at \(J = 3.7 \times 10^3 \text{ MNm}^{-2}\) crack resistance behaviour increases with loading rate. So a conservative estimation of fracture behaviour can be made by a quasistatic \(J_R\)-curve.

REFERENCES

Fig. 6: Comparison of calculated and experimentally observed stable crack growth values

Fig. 7: $J_R$-$\Delta a$-curves as a function of loading rate