INFLUENCE OF MICROSTRUCTURE ON TOUGHNESS OF A STEEL 20 MnMoNi 5 5

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Four types of microstructure resulting from different cooling rates have been studied in tensile tests with round unnotched, double-notched bars, in charpy-V-, fracture mechanic- and wide plate tests. The fracture behaviour was similar in all testing conditions. In the lower toughness regime K_{Ic}-values are predicted using the RKR-model, and compared with measured values of CT-specimens and wide plate tests.

The microstructure of heat treated steels has an important influence in the fracture behaviour of steels. To evaluate the influence of different heat-treatment on the toughness and strength of the structural steel 20 MnMoNi 5 5 four types of microstructure resulting from different cooling rates after austenitising have been studied in tensile tests with round unnotched and double-notched bars, in charpy-V-, fracture mechanics-, and wide plate tests. By the various testing techniques the fracture behaviour was studied in the temperature range from 77 K up to 333 K correlating results of small specimens with wide plate tests.

MATERIAL

The pressure vessel steel 20 MnMoNi 5 5 (steel B) was tested in four different heat-treated conditions. Fig. 1 shows the chemical composition, the different heat-treatment, and the resulting microstructure. Plate B1 (water quenched) and plate B2 (oil quenched) show the typical acicular heat-treated structure resulting in a coarser carbide distribution as a result of the slower cooling rate. The microstructure of plate B3 is similar to one caused by soft annealing and plate B4 shows an extremely banded structure with bands of preeutectic ferrite and bands of bainite and martensite with high carbon content. Slowing down the cooling rate results in coarser carbide-distribution and coarser grain structure. The austenite grain size according ASTM is class 10/11 and the mean ferrite grain size in the banded structure is 7-8µm.

The results of tensile tests of unnotched round bars at room temperature and 77 K and of the charpy-V-tests are summarized in

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fig. 2. The characteristic data ($R_{p\ 0,2}$, R_m, A, Z) of the tensile test show a general tendency: the yield and the tensile strength ($R_{p\ 0,2}$, R_m), the reduction of area (Z) and elongation after fracture (A) increase at room temperature and at 77 K with increasing cooling rate. The water quenched plate B1 shows at room temperature a lower yield stress of R_{eL} = 730 MPa with a reduction of area after fracture of Z = 65 % whereas the retarded air cooled plate B4 has a yield stress of $R_{p\ 0,2}$ = 580 MPa and a reduction of area after fracture of Z = 55 %. Compared to room temperature the characteristic data of strength $R_{p\ 0,2}$ and R_m increase at 77 K whereas toughness data Z and A decrease.

In the charpy-V-test the tendency of higher toughness values with increasing cooling rate is also to be seen. In the upper shelf regime charpy-energy $A_{v\ max}$ increases from 110 J for plate B4 to 160 J for plate B1. The tensition temperature for 50 % of the upper shelf value $T_{T\ 0,5\ A_v\ max}$ is also influenced by the cooling rate. With increasing cooling rate T_T decreases from 315 K (plate B4) to 185 K (plate B1).

FRACTURE MECHANIC TESTS

In order to characterize the toughness behaviour of the four plates fracture mechanic tests were carried out of 28 mm thick and 100 mm wide compact specimens with an a/W-ratio of 0,5 in a temperature range from 77 K to 333 K. In fig. 3 the fracture toughness K is presented as a function of temperature T for the plates B1, B2, B3, and B4. Above the ASTM-geometry transition temperature I K_{max}- values are calculated and above the temperature for the beginning of stable crack growth III K_{Ii}-values are calculated also. All plates show an increase in toughness K with increasing temperature but there is a shift in transition temperature as well for the ASTM-criterion as for the beginning for stable crack-growth to higher temperatures with decreasing cooling rates. The region of linear-elastic fracture mechanic is extended from T = 128 K for plate B1 to 212 K for B4. Stable crack growth starts at 172 K in the water quenched condition and at 294 K in the retarded air cooled plate. The tendency of decreasing toughness with decreasing cooling rate is also to be seen in fracture mechanic tests.

WIDE PLATE TESTS

The wide plate tests were carried out on 450 mm wide and 30 mm thick plates with a 30 mm long fatigue crack. 6 specimens from each of the different heat-treated plates were tested in the temperature range between 173 K and 293 K. The loading direction of the specimens was transverse to the rolling direction in the plates. During the tests the load, the overall elongation on a measuring base of 450 mm and the crack opening were recorded. From that stresses and strains at yield point, maximum load and fracture were determined. The tests were carried out on a servohydraulic 12 MN-test rig with which the fatigue crack was also brought in the wide plate specimens (1),(2).

Deformation behaviour of center cracked wide plate specimens

The experiments and the results of some finite element calculations have shown that the stress state of the wide plates is plane stress. The plastically deformed areas in wide plate specimens are quite different from the plastic zones of other cracked specimens with regard to there shape and extension. This is due to the specific geometry and the kind of loading of the wide plates. Only at low stress levels the shape of the plastic zone is similar to that in a CT-specimen.

The main extension of the plastic zone is observed under an angle of 45^{o} - 50^{o} to the loading direction as it is shown in fig. 4a for a stress lower than the yield stress in the notched area. If the stress is increased up to flow stress the plastic zone is mainly extended along an angle of about 45^{o}, until the edge of the plate is reached (fig. 4b). At this point which is identical with the yield point of the wide plate, a great area in the ligament is only elastically deformed. These experimental results from optical observations and measurements with moiré-grids are approved by finite element calculations (3). If the wide plate is deformed further the whole V-shaped area will be plastically deformed. Only if the crack is small in comparison to the width of the specimen, the yield strength of the material is also reached in the unnotched area and plastic deformation not only occures in the notched area (net section yielding), but also over the whole length of the specimen (gross section yield) (fig. 4c). Gross section yielding is depending on the test temperature and the geometry of the wide plates as width and crack length.

Influence of temperature on the fracture behaviour of the wide plate specimen

The temperature has a strong influence on the fracture behaviour of ferritic steels especially if specimens with cracks were tested. This influence of temperature is illustrated in figs. 5 and 6. Four temperature regions can be defined. At low temperatures the fracture of the specimen occures at stresses lower than the yield stress of the wide plates. At a certain temperature the fracture starts at a stress level equal to the flow stress. The lowest temperature at which the fracture stress reaches the flow stress is called T_{gy}. The plastic zone has reached the plate edges prior to fracture. With increasing temperature the strains, measured on the wide plates, are increasing, but the fracture surface shows only cleavage fracture. This region is limited by the transition temperature T_i at which the first amount of ductile, stable crack growth at the crack tip is observed.

The temperature T_a is the lowest temperature at which the specimens show a fully ductile fracture behaviour; on the fracture surfaces no cleavage fracture can be observed. Between T_i and T_a the amount of ductile crack growth increases with increasing temperature. The transition temperatures depend on the toughness of the material. The transition temperature T_{gy} of the delayed cooled plate B4 is, for example, 250 K, T_i 293 K; fully ductile fracture behaviour was not observed in the investigated temperature range (fig. 5). For the oil-quenched and tempered plate B2 T_{gy} is lower than 173 K, T_i is 203 K and fully ductile fracture behaviour was observed at 193 K (T_a), as it is shown in fig. 6

COMPARISON OF THE TRANSITION TEMPERATURES OF SMALL SCALE AND LARGE SCALE SPECIMENS

Tests were carried out with charpy-V-impact specimens, CT-specimens, sharp-notched bend specimens, and wide plate specimens. Due to the different kinds of loading it is not possible to compare directly the results of the different types of specimens. Therefore, the comparison was made on the basis of the transition temperature T_i which was determined for the wide plate tests, the fracture mechanic tests and the sharp-notched bend tests. From the charpy-V-test the transition temperature $T_{T_{A_{vmax}}}$ was chosen, from the drop weight-tests the NDT-temperature. In fig. 7 the transition temperatures T_i for the different types of specimens and NDT are shown in dependence from $T_{TAvmax/2}$. The shifting of transition temperatures T_i due to the change of microstructure and toughness is similar for all types of specimens. The accordance between the shift of the T_i from the wide plate test and the shift of $T_{TAvmax/2}$ is very good, the shifting of the temperatures T_i of the fracture mechanic tests and sharp-notched tests is greater than $T_{TAvmax/2}$, the shift of the NDT-temperature smaller. The differencies between the transition temperatures T_i, determined in the fracture mechanic tests, and between the NDT-temperatures of the plates B3 and B4 is much more smaller than the differencies between the transition temperatures, determined from the other specimens.

A similar shift of the fracture behaviour due to the change of microstructure of this steel is shown from all types of specimens. But it is not possible to compare different types of steels only on the basis of $T_{TAvmax/2}$ or another transition temperature of small scale specimens in respect to the fracture behaviour of the large scale specimens.

MICROSCOPIC CLEAVAGE STRESS

To evaluate the brittle fracture behaviour of the four plates, the microscopic cleavage stress σ_f^* was determined. Tests with double-notched tensile specimens were carried out in a temperature range from 77 K to 223 K to determine the fracture stress σ_f and the stress as general yield σ_{gy}. In fig. 8 the stresses σ_f and σ_{gy} are presented at a function of temperature for plate B3 and B4. In the forced-air cooled condition the fracture stress σ_f and the stress at general yield σ_{gy} are lower in the whole temperature range. There is also a shift of the temperature T_{gy} where general yield occurs in the ligament of the specimen to higher values with decreasing cooling rate. In the region of low-stress fracture two dimensional finite element calculations (4) using isoparametric eight nodal elements were made to determine the microscopic cleavage stress σ_f^*. For plate B3 and plate B4 the microscopic cleavage stress was calculated to σ_f^* = 2155 MPa and σ_f^* = 2032 MPa, respectively.

Correlation of the microscopic cleavage stress with fracture mechanics- and wide plate tests

Failure at the lower shelf toughness has been modeled as slip-initiated cleavage fracture using the critical stress criterion proposed by Ritchie, Knott, and Rice (RKR-model (5). This model indicates that cleavage cracks propagate in an unstable manner when the maximum principal tensile stress σ_{yy} ahead of a notch exceeds a critical value σ_f^* over a characteristic distance x_c. Accordingly the low temperature toughness can be related to the material's yield and fracture stresses. By using Tracey's (6) stress distribution for work hardening material behaviour fracture toughness values can be predicted. In fig. 9 the comparison between predicted and measured values for K_{Ic} is presented as a function of temperature. In the temperature range from 77 K up to 213 K there is a good agreement between predicted K_{Ic}-values and K_{Ic}-values measured with CT-specimens and wide plate tests for the plates B3 and B4.

CONCLUSIONS

Four types of microstructure resulting from different cooling rate have been studied. The different strengths and toughnesses were investigated in tensile tests with round unnotched and double-notched bars, in charpy-V-, fracture mechanics-, and wide plate tests. The influence of the different microstructures of this steel on the fracture behaviour was similar in all testing conditions. In the lower toughness regime the prediction of K_{Ic}-values using the RKR-model was in good agreement with measured K_{Ic}-values from fracture mechanics- and wide plate tests.

SYMBOLS USED

A	= elongation after fracture (%)
$A_{v max}$	= charpy energy in the upper shelf regime (J)
K_i	= fracture toughness at initiation of stable crack growth ($MNm^{-3/2}$)
K_{Ic}	= fracture toughness ($MNm^{-3/2}$)
K_{max}	= fracture toughness at maximum load ($MNm^{-3/2}$)
R_{eL}	= lower yield stress (MPa)
$R_{p\,0,2}$	= yield stress (MPa)
R_m	= tensile stress (MPa)
σ_f^*	= microscopic cleavage stress (MPa)
σ_{GS}	= gross section stress (MPa)
σ_{NS}	= net section stress (MPa)
σ_Y	= flow stress (MPa)

σ_{yy}	= principal stress (MPa)
T	= temperature (K)
T_a	= temperature for fully ductil behaviour (K)
T_{gy}	= temperature for general yield (K)
T_i	= temperature for the beginning of stable crack growth (K)
$T_{T\ 0,5\ Avmax}$	= transition temperature for 0,5 A_{vmax} (K)
Z	= reduction of area after fracture (%)

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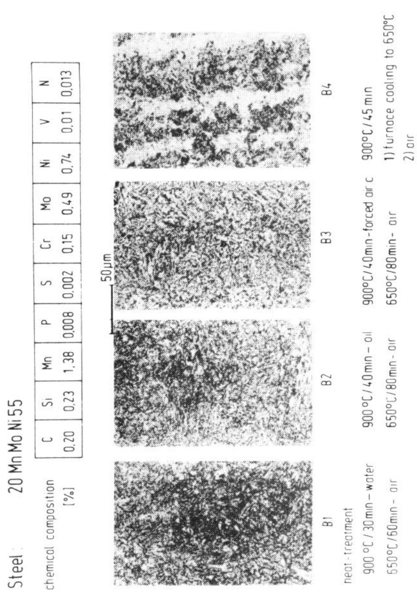


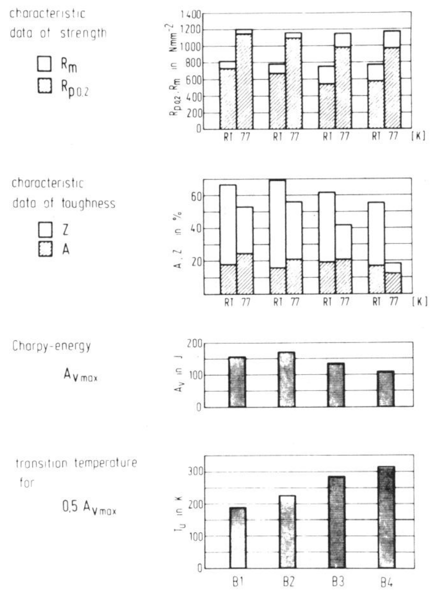
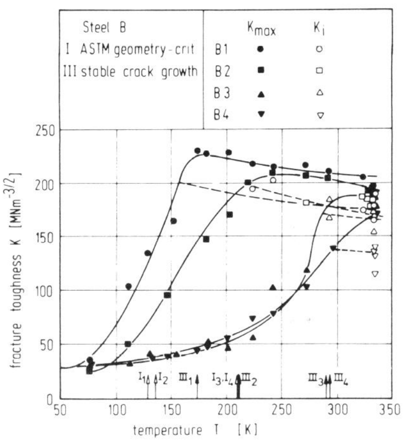


Fig.1 Microstructure and heat treatment of steel B

Fig.2 Characteristic data of tensile and charpy-V-tests



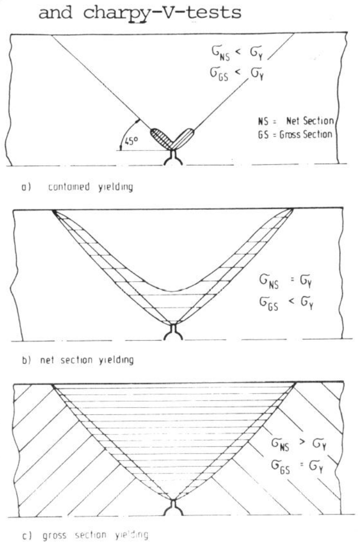


Fig 4 Development of plastic zone in center notched wide plate specimen

Fig.3 Fracture toughness K as a function of temperature

Fig. 4 Development of plastic zone in center notched wide plate specimen

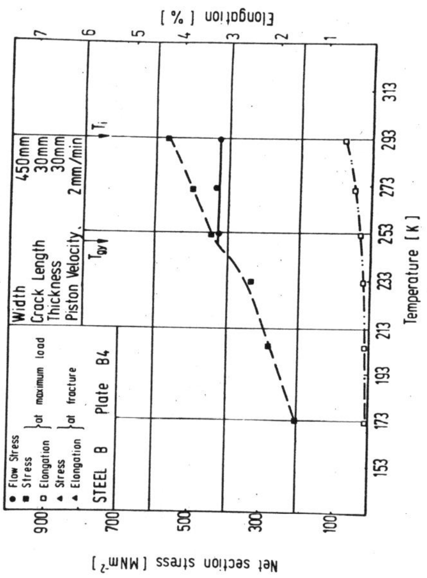


Fig.5 Net section stress and elongation as a function of temp.for a wide plate specimen

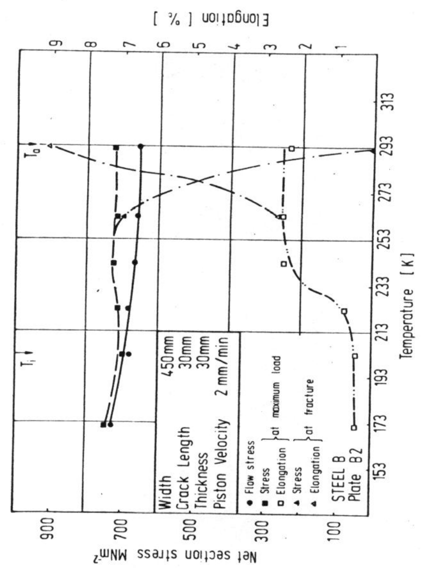


Fig.6 Net section stress and elongation as a function of temp.for a wide plate specimen

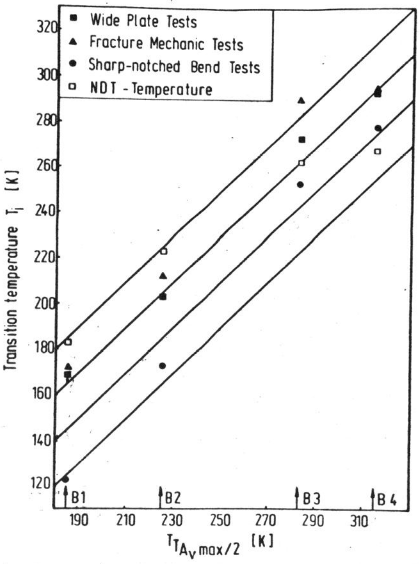


Fig.7 Correlation between different transition temperatures

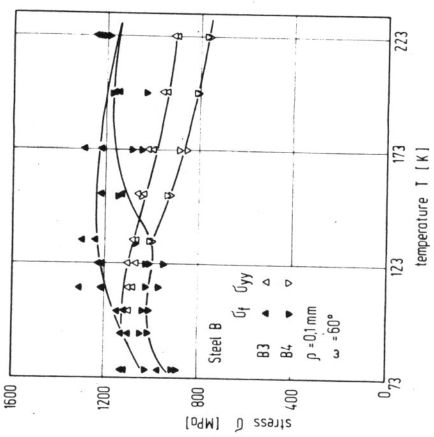


Fig.8 Net section stress as a function of temp.for a double-notched specimen

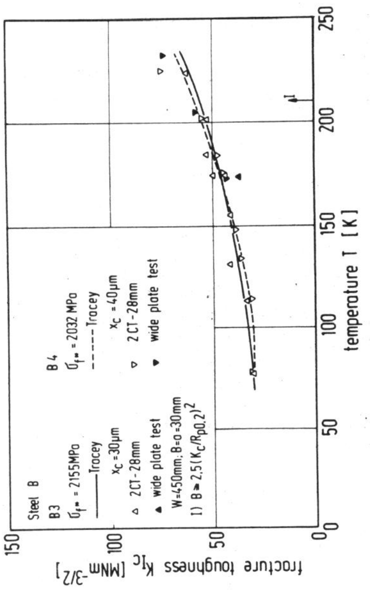


Fig.9 Comparison of predicted and meas- ured K_{IC}-values as a function of temp.