APPLICATION OF FRACTURE CONCEPTS TO STEEL 42 CR MO 4 IN DIFFERENT HEAT TREATED CONDITIONS

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ABSTRACT

Steel 42 Cr Mo 4 in different heat treated conditions, covering a hardness range from 190 to 640 HV1 has been examined in conventional and fracture mechanics tests. The results on smooth, notched and precracked specimens under static and dynamic loading are partly contradicting with respect to a safety judgement of the material states. Obviously the safety requirements respectively the applied concepts should be specificly related to the actual service loading conditions, which may be load, displacement or energy controlled.

KEYWORDS

Hardness; notch tensile strength; instrumented C_v-test; post-yield fracture mechanics; failure assessment diagram; safety concepts

INTRODUCTION

Design and safety analysis of components are primarily based on conventional concepts, which are founded on adequate strength and toughness of the material. These properties are enabling furthermore a qualitative safety judgement for sharp notched and cracked components, because the response of those structures to the applied load is governed by toughness. For a more detailled quantitative analysis the different fracture mechanics methods.

A unique safety statement on the basis of all these properties remains problematic insofar that the specimens used were not only differing in the stress state (kind of defect, size) but also in loading velocity (static, dynamic). One of the most crucial points is especially associated with the significance of conventional strength and toughness properties (e.g.C_v-energy) with respect to a safety statement for cracked structures.

The objective of this paper is to expose this problem in evaluating the results of tests on smooth, notched and precracked specimens of a steel in different states of strength and toughness. These various microstructures were systematically generated by different heat treatment procedures and characterized by their hardness levels.

MATERIAL AND HEAT TREATMENT

The material investigated was a chrom molybdeniumsteel 42 Cr Mo 4 (DIN 17 200), which was delivered in bars whith cross section 30 x 500 mm² in tempered state. The chemical composition, Table 1, was in accordance with the required values. The hardness in the as delivered state was 190 HV10.

TABLE 1 Chemical Composition of Material 42 Cr Mo 4

	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
Required (DIN 17200)	0,38 - 0,45	0,25	0,65	≤0,035	≤0,035	1,0	–	0,2	–	-
Obtained	0,41	0,25	0,66	0,008	0,024	1,03	0,28	0,17	0,31	0,01

In order to obtain different hardness levels the machined specimens were heated above the austenitising temperature (850 °C, 1 h) and subsequently cooled down with different cooling rates, quenching the specimens in water and oil, as well as cooling in air. The temperature-time-history was recorded with Ni Cr-Ni thermocouples located on the surface and at the centre of the specimens. Figure 1 shows the obtained cooling curves in the time temperature transition diagram.

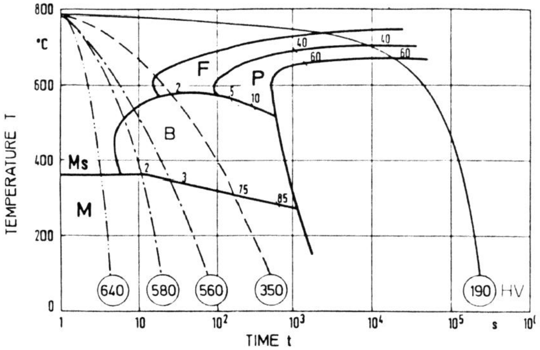

Fig. 1. Time Temperature Transition Diagram of 42 Cr Mo 4 with cooling lines

The corresponding hardness values are marked Fig. 1 and given in Table 1 for the different specimen sizes.

TABLE 2 Heat Treatment and Hardness Values

	Hardness HV1 after cooling in				
Specimen Cross Section	Water	Oil	Compressed Air	Air	As Delivered
10 x 10 mm²	640	580	560	350	190
25 x 50 mm²	550	410	340	-	190

The hardness levels, covered in the investigation, ranged from 190 HV to 640 HV. The hardness distribution was almost homogenuous across the cross sections. The microstructures are characterized by coagulated cementite (190 HV), upper and lower bainite (300 HV to 500 HV) and martensite (>550 HV).

TENSILE TESTS

Tensile tests were carried out at room temperature on smooth and notched round bars. The results of smooth specimens (8 mm Ø) in Fig. 2 are showing with increasing hardness the expected nearly linear increase of strength properties (ultimate R_m, yield R_p) in connection with a decrease of toughness properties (reduction of area Z, elongation at fracture A_5, elongation before reduction A_g). The correlation factor R_m/HV1 was found to be about 3.

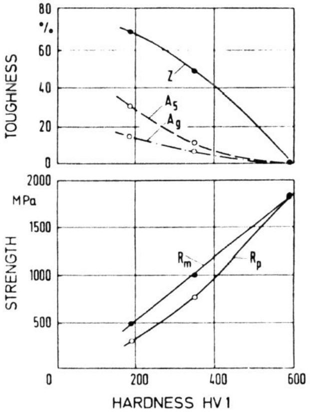

Fig. 2. Results of tensile tests on smooth specimens

The notch tensile strength was determined on round bars with V shaped (60°) circumferential notches with different radii giving a stress magnification factor of α_k = 1,3 and 2.1. The net cross sections were identical to those of the smooth bars. The nominal net fracture stress is given in Fig. 3 as a function of hardness. In addition the results of the smooth bars and the precracked three point bending specimens are plotted in the diagram.

It could be demonstrated that loadability increases with hardness for the unnotched and smooth notched specimens. The fracture stress of the sharper notched specimens is characterized by a maximum loadability at about 350 HV. The maximum constraint factor was found to be about 2.5 turning into values less than 1 for hardnesses >500 HV, approaching the theoretical linear elastic value of 1/α_k for the highest hardness numbers. The nominal fracture stress of the fracture mechanics specimens are - comparable to the toughness properties in tensile tests - steadily decreasing with increasing hardness.

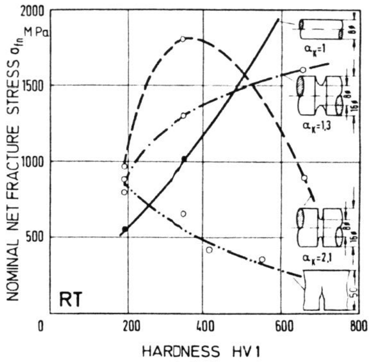

Fig. 3. Results of tensile tests on smooth and notched specimens

NOTCH BAR IMPACT TESTS

The results of notch bar impact tests, carried out on standardized C_v-specimens, are plotted in Fig. 4. The C_v-energy versus temperature-diagrams are demonstrating that increasing hardness yields in a pronounced decrease of upper shelf energy and an increase of transition temperature.

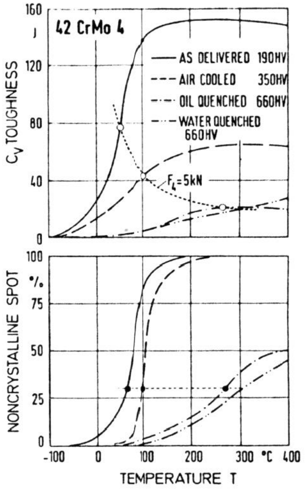

Fig. 4. Results of notch bar impact tests on C_v specimens

The force-deflection-records of the instrumented C_v-tests, examples in Fig. 5, had been used to determine the NDT-temperature on the basis of the F_4-criterion (Berger and other 1979). The crack arrest conditions - defined as F_4 = 5 kN-are indicated by circles in Fig. 4. Again a higher hardness is connected with a higher NDT-temperature. It should be noted that the points of crack arrest are situated at different C_v - levels and are shifted towards the upper shelf regime for the low shelf material state. Crack arrest is obviously associated with a certain amount of shear lips. This can be seen by the noncrystalline spot line(Fig. 4 below), which ended for all material states at the NDT-temperature in a constant percentage of about 30 %.

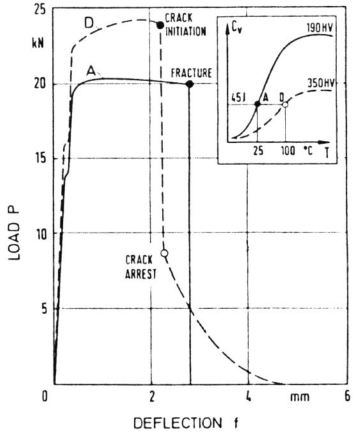

Fig. 5. Load-deflection-diagrams for specimens of same C_v-energy

FRACTURE MECHANICS INVESTIGATION

Fracture mechanics tests were carried out on standardized three-point-bending specimens of 25 mm thickness and 50 mm width. Measuring crack opening displacement (COD) as well as load line displacement (LLD) enabled the evaluation according to ASTM E 399 (fracture toughness K_{Ic}), ASTM E 813 (J integral) and BS 5762 (crack tip opening displacement CTOD). The test results at room temperature and 100 °C are summarized in Table 3. It should be emphasized that for the J-evaluation on three point bending specimens the LLD values have unconditionally be corrected by the elastic plastic indentations at the load application points. The corrected area under the load-LLD-diagrams for low hard material states deviated up to 30 % from the uncorrected values.

TABLE 3 Results of Fracture Mechanics Tests

Specimen	Hardness HV 1	Temperature °C	Fracture Toughness MPa $\sqrt{m}$	J Integral kJ/m² J_{el}	J_{tot}	CTOD mm δ_{el}	δ_{tot}
A	190	25	96 $^{1)}$	40	105	0,058	0,182
B	190	100	116 $^{1)}$	58	800 $^{2)}$	0,085	1,10 $^{2)}$
C	350	25	73	25	25	0,017	0,017
D	350	100	112 $^{2)}$	54	68	0,036	0,081
E	410	25	37	6 $^{3)}$	6	0,0033 $^{3)}$	0,0033
F	550	25	35	4 $^{3)}$	4	0,0013 ^{3}	0,0013

$^{1)}$not valid acc.ASTM E 399 $^{2)}$first attainment of max.load $^{3)}$calc. from K_{Ic}

The correlation of hardness and fracture properties in terms of J and CTOD for room temperature is given in Fig. 6. Increasing hardness causes steadily decreasing J-and CTOD-values, which is again in qualitative accordance with the toughness properties determined in tensile and C_v-tests. The curves for the elastic parts J_{el} and $CTOD_{el}$ are indicating that material states exceeding 400 HV are behaving totally elastic until fracture. The correlation factor of J and CTOD was found to be in the range of 1.5.

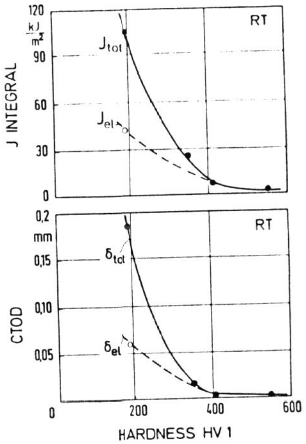

Fig. 6. Results of fracture mechanics tests at room temperature

The fracture mechanics tests at room temperature were extended to 100 °C in order to observe the fracture toughness of different material states having the same C_v-toughness. As shown in Fig. 4 and 5 this is the case for 190 HV at room temperature (specimen A *) and 350 HV at 100 °C (specimen D*). The corresponding diagrams of fracture mechanics tests, plotted in Fig. 7 are showing in principle a similar load-deformation-characteristic than those of the instrumented C_v-tests (Fig. 5). The material state of higher hardness is responding in a higher load level and a reduced deformation at fracture. However the evaluation of CTOD and J (see specimen A and D in Table 3) resulted into clearly different fracture toughness in the CTOD values, where for specimen A (190 HV) it was found to be more than the double as compared to specimen D (350). These results are remarkable insofar that they are contrary to the fracture mode in C_v-tests, where specimen A* failed in a more brittle state than specimen D* (see noncrystalline spots in Fig. 4). Due to the fact that the properties of fracture mechanics tests were in accordance with the upper shelf energy of C_v tests the results can presumably be explained by a shift of transition temperature of the dynamic C_v-tests compared to the static fracture mechanics tests.

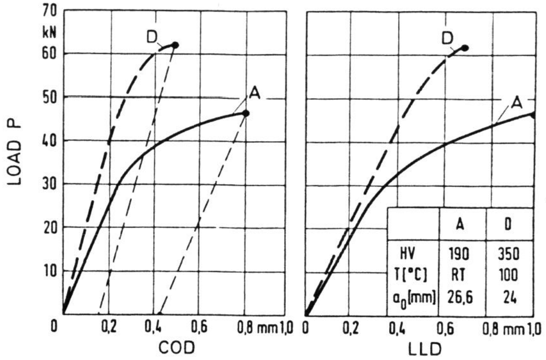

Fig. 7. Load-deformation characteristic for material states of same C_v-energy (see Fig. 5)

The equations of the Ductile Fracture Handbook (Kumar, German, Shih, 1981) were used to calculate the J Integral values for the three-point-bending specimens with a hardness of 190 HV and 350 HV. The strain hardening parameters and n were determined using the Ramberg-Osgood approximation of the flow curve. The numbers are given in Fig. 8 together with the J-load-diagrams calculated for plane strain condition. The experimentally evaluated J values for specimens A, C and D are in good agreement with the calculated lines. Specimen B, which failed in collapse, indicates that the collapse load P_L for three-point-bending-specimens is underestimated in the Handbook.

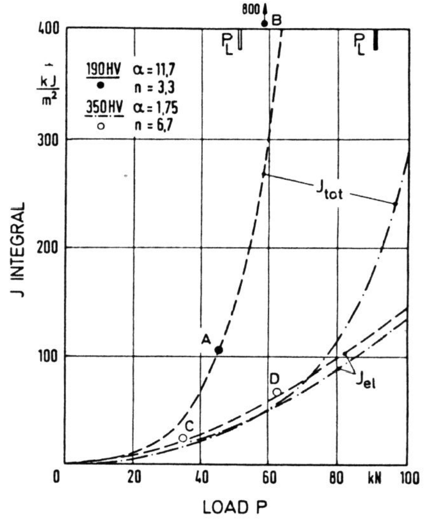

Fig. 8. Driving force curves for specimens A and D compared to results of fracture mechanic tests

FAILURE ASSESSMENT DIAGRAM

The results of the fracture mechanics tests were used to observe the validity of the Failure Assessment Diagram (FAD). Fig. 9 presents the test results in the unmodified as well as the modified FAD. The evaluation was based on the limit load equation and the elastic and plastic J-values calculated according to the Ductile Fracture Handbook, see Fig. 8. The modification of FAD was made for 190 HV and 350 HV material state using the strain-hardening parameters of Fig. 8.

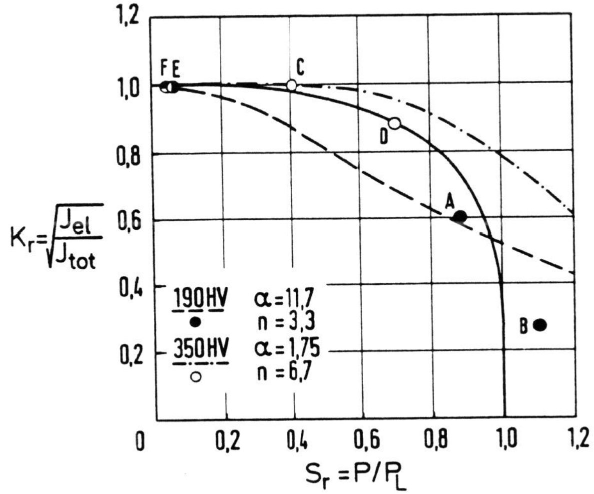

Fig. 10. Test results in the unmodified and modified FAD

The unmodified FAD conformed to the test results with the exception of specimen A, whose fracture load is underestimated by about 5 %. However on comparing with the modified line this underestimation is corrected (see also Fig. 8). But it has to be considered that now the collapsing specimen B is distinctively underestimated, which can be explained by a nonaccurate theoretical limit load.

CONCLUSIONS

On the basis of fracture tests carried out on steel 42 Cr Mo 4 in different heat treated conditions the following conclusions can be drawn:

- Increasing hardness is associated with an increase in strength of unnotched and smooth notched specimens. At the sharper notched specimens a maximum loadability was observed at a medium hardness of about 350 HV. For the cracked specimens the fracture stress was steadily decreased with increasing hardness.
- C_v-temperature behaviour is characterized by an increase in transition temperature and a decrease of upper shelf energy with increasing hardness.
- The NDT-temperature - determined with the F_4-criterion - is correspondingly increased with hardness. NDT-temperature, respectively crack arrest, seems to be governed by the formation of shear lips and not by C_v-energy. Consequently crack arrest in C_v-tests occured for high shelf material state in the transition range, for low shelf materials in the upper shelf regime.

- J and CTOD values are decreased with increasing hardness. Hardness levels above 400 HV yielded in a linear elastic fracture behaviour of 25 mm thick bending bars.
- The test results could be used for the validation of the J calculation according to the Ductile Fracture Handbook and the Failure Assessment Diagram in the unmodified and modified version. The discrepancy between theoretical prediction and experimental results are obviously related to the proposed limit load equation.
- The partly contradicting toughness requirements could be demonstrated in fracture mechanics tests on 2 material states with the same C_v-energy, which ended in clearly different CTOD- and J-values. This result enlightens the problem of using C_v-energy as an unique safety criterion and to correlate C_v to fracture mechanics in the transition range.
  But even when using fracture toughness values a more detailled analyses on the bases of the load-deformation characteristic seems to be necessary, considering the actual loading conditions, which may be load, displacement or energy controlled. Based on the present results, material state A should be selected with respect to displacement and energy controlled events, due to the higher deformation at fracture (COD, LLD) and the energy consumption (J). On the other side material state D with the higher fracture load and crack arrest capability seems to be more favourable according to primary stresses and crack arrest.

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