BEZIEHUNGEN ZWISCHEN KERBSCHLAGZÄHIGKEIT, ROBERTSON-VERSUCH UND DROP-WEIGHT TEST

(THE RELATIONSHIP BETWEEN NOTCHED BAR IMPACT BENDING TEST, ROBERTSON-TEST AND DROP-WEIGHT-TEST)

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SUMMARY

For the safety analysis of structures against brittle failure in most cases a combination of linear-elastic fracture mechanics and NDT-temperature is used. The latter is esteemed as a border temperature; if the temperature falls below, brittle fracture may occur. It is determined with the Drop-Weight-Test (DWT, according to ASTM E 208-69), substitutionally or for control with the notch impact bending test. Thus the temperature of the ISO-V notch impact strength 8.7 kpm/cm^2 may not exceed 33°C over NDT, as per ASME-PVC III, App. G (1972). The same range is proposed as safety against brittle fracture with tests (for instance pressure tests). The Robertson-Test determines the temperature, where a propagating crack is arrested. Supposing, a crack is initiated at an unfavourable part of the structure and does not lead to fracture if caught in tough matrix after a short distance, the temperature defined by the Robertson-Test is of decisive importance. Tests with the steel 22 NiMoCr 37 show no correlation between the crack arrest temperature of the Robertson-Test, DWT and the notch impact strength. A NDT temperature of -30°C was determined with the DWT, whereas a temperature of $+30$ to 35°C resulted in the Robertson gradient test, when the mode of fracture shifted. On the other hand, the temperature of the 8.7 kpm/cm^2 notch impact strength was below the 33°C limit ($\text{NDT} + 33 = +3^\circ\text{C}$). The examination of the fracture surfaces in the scanning electron microscope (SEM) yielded the following result: with the Robertson gradient test the fracture shifts from cleavage to ductile dimpled fracture. Supposedly, a reduction of fracture speed should result. But the crack did not arrest before the temperature had reached $+61^\circ\text{C}$, when the fracture had already shifted into a shear mode. Caused by the resulting macro-deformation, the stress fell below the critical value. There is no corresponding shift with the DWT at -30°C . Comparing tests with specimens having the full wall thickness of the Robertson specimens (30 mm) show, that the cracked area diminishes with increasing temperatures. Even at $+10^\circ\text{C}$ cleavage still is dominant, although the cracked area is small. It seems more favourable to define the NDT temperature by another criteria than specified in ASTM, or to use a larger temperature addition for brittle fracture safe structures, than given by ASME. This, for instance, may be the temperature corresponding to the crack arrest immediately behind the hard tack weld, if a definition by SEM is abandoned for technical reasons. A corresponding comparison with notched bar impact bending test specimens is less clear, as here the amount of cleavage in the fracture surface is influenced to a great deal by the size and the previous deformation of the specimen.

1. Introduction

Safety against brittle failure is a predominant question, since the tensile strength of steels was increased during the last few years and also larger wall thicknesses were needed to meet the requirements for design. The danger originates rather from the (in many cases inevitable) weldments than from the base material, although the composition of the base material is of substantial importance for the strength behaviour of the welded structure. The other factors are - besides temperature and stress - welding process (electrode, granular flux, shield gas, preheat/interlayer temperature, post-weld heat treatment) and shape of the component. The welding defects of different kinds including local embrittlement, which have to be calculated with, may possibly cause a brittle or ductile catastrophic failure. The fracture mode may be crystalline, cleavage (with dimples) or shear/fibrous. It is tried to determine the strength behaviour of components by ways of the LEFM; for tougher materials the theory was based upon the COD concept. The difficulties are mainly to use the adequate fracture toughness values and to involve residual stresses which can up to now be only considered empirically by failure analyses [1].

This is one of the reasons for not only determining the fracture toughness K_{Ic} with the static test, but also, as K_{Id} , with the dynamic test; analogously the ability of a material to arrest a running crack was defined as K_{IA} or by other tests (e.g. Robertson Test) [2]. In the USA the fracture mechanics technology has together with the NDT concept already led to the regulations in ASME-PVC III, App. G, which are not yet obligatory. The NDT temperature is to be defined by the DWT and controlled by the Charpy-V notched bar impact bending test. As all these tests follow the same physical rules - although application varies - there must exist a correlation between them and this is examined below. Furthermore, it needs to be checked, what statements these test results will render with regard to the mentioned modes, especially crack arrest.

2. Robertson Test

The isothermal and gradient Robertson Test [3] proceeds as follows: the "short" specimen (fig. 1) is stressed in a tensile machine (the stress normally being $2/3 \sigma_y$ approx.). The crack is initiated at the deepfrozen nose by impact. The crack propagates across the specimen width or is arrested. The temperature at which the crack is arrested is the decisive one. This temperature can be estimated with the gradient and then confirmed by the isothermal test.

Table 1 gives the test conditions and results of 7 tests with the steel St 37, which were performed at the MPI Düsseldorf [4]. In order to throw light upon the influence of the latent elastic energy - and thus the stress - on the fracture behaviour, parallel tests were conducted at the MPA Stuttgart but with very long specimens (total length 13,5 m), Fig. 2.

The test conditions and results are also given in Table 1. It became evident that obviously - regardless of the length of specimens (and the machine) - the temperature is the decisive factor for the crack arrest condition. The reason for this is, that a certain minimum stress (which cannot be determined by the Robertson test for reasons of the superimposed bending oscillations) is necessary to maintain the crack in the shear mode. Further tests with the steel 22 NiMoCr 37 (similar to A 508 Cl. 2) which is commonly used for reactor pressure vessels are also listed in Table 1. The specimens were taken from a 143 mm thick plate either near the surface or from the centre part. The unbroken specimens were cooled down and then fractured. The fracture surfaces show the characteristics of a crystalline fracture Fig. 3. The fracture face of specimen no. 14 (Fig. 4) is remarkable. At first the fracture shifted from a crystalline fracture to a "dull" border at +34 °C approx., then changed again to the crystalline mode, to be converted once more into a "dull" fracture at + 54 °C. Then a shear fracture followed. At + 61 °C the crack arrested, Fig. 5.

The microfractographic examination confirmed, that the crystalline fracture face is mainly of cleavage type, Fig. 6 and 7. At its transition to shear fracture the dull fracture face shows the typical ductile dimple structure, Fig. 8. As follows from the metallographical examinations the structure of zones a and b in Fig. 5 differ slightly. The cleavage fracture passes through a region of characteristically mixed ferritic/bainitic structure, Fig. 9 and 10; where dull fracture is given, fine grain structure with low ferrite percentage dominates, Fig. 11. It thus can be concluded from the aforesaid findings that the fracture behaviour is determined by the temperature and the (multiaxial) stresses whereas the speed ensues from the fracture characteristics. Cleavage runs with a higher speed (up to 1,5 km/sec) than ductile fracture. The arrest of ductile fracture depends primarily on the effective stress, and that stress again is determined to a great deal by the fracture mode and the resulting macro deformation. If this assumption is correct, other tests must yield the same conclusions. For comparison, further tests with drop weight specimens and notched bar impact bending specimens of the same material 22 NiMoCr 37 were performed.

3. Drop Weight Test (DWT)

ASTM E 208 regulates this test [5] for 3 different specimen sizes P 1 - P 3. The specimens are bent by impact with bending values depending on the thickness. On the tension surface a brittle and notched bead is welded. The temperature of the specimens is varied; the temperature, where the fracture does no longer arrest, is taken as NDT temperature. As an additional requirement 2 specimens are not permitted to fracture at a temperature 5 °C above NDT. It is stated that the specimen's thickness and the direction of rolling do not influence the NDT temperature.

Tests with specimens P 3 ($50 \times 16 \text{ mm}^2$), that were taken from a 240 mm thick plate of material 22 NiMoCr 37 yielded a NDT temperature of -30°C as per the aforesaid definition. The discrepancy to the result of the Robertson specimen is remarkable. This can be thus explained: even at low temperatures, the fracture faces of the Robertson specimen show shear lips at the borders which enlarge near the transition, Fig. 5. This fact is attributed to the multiaxial stress conditions and the resulting restraint. The DWT does not take this into account. Due to the rather small bending value, a crack can be arrested even when the fracture is fairly brittle. This is the case, when in the cracked area the bending stress has declined so far that the necessary force can be hold. This force can also be defined by fracture mechanics tools.

Fig. 12 shows 3 cases. The deflection curve 0 is assumed without crack. Case 1 has a crack in the initiation bead, which is arrested in the HAZ; the appropriate fracture mechanics curve F-COD (on the right of Fig. 12) yields a maximum force higher than the force which is necessary to deform the bending specimen up to the limit f_g : the crack arrests. In case 2, a larger crack is assumed, that diminishes the bending stress to a great deal (dash-lined). This crack might arrest according to the K_{IA} - value and the corresponding crack size. If more force is applied a further bending deformation may ensue till the K_{Id} value is exceeded. It should thus be possible to determine a crack arrest value K_{IA} with this modified DWT; but edge effects and shock waves are so dominant, that no authentic definition seems practicable.

Further specimens of the full thickness of 30 mm (other dimensions same as the P 3 specimen) were taken from the broken Robertson specimen 14 and from the original plate. Due to the larger thickness, a free bending value of 1,5 mm was intended but later increased up to 1,9 mm. Test conditions and results are shown in Table 2. At a temperature of $+30^\circ\text{C}$ the bead did only tear when the bending reached 1,9 mm, but the crack was arrested. After a further stroke at -10°C (new bending with fixed 1,9 mm), rupture ensued. Fig. 13 shows that the crack arrested at $+30^\circ\text{C}$ in the HAZ of the tack weld DUR 400 (dull fracture). The fracture face was crystalline at -10°C .

At $+10^\circ\text{C}$ the crack was also arrested in the HAZ; at $\pm 0^\circ\text{C}$ (second stroke) it propagated into the base material, Fig. 14. The first stroke $\pm 0^\circ\text{C}$ yielded a similar result. The main characteristic of the fracture face at either -10°C or $+10^\circ\text{C}$ was cleavage. The HAZ always showed dimples, the same goes for the border zone, where the crack arrested. A cut in specimen 2 proves that HAZ and the tough border are in fact identical.

In order to by all means enforce a fracture, extending the HAZ, the bending value of the specimen was not limited, as given by ASTM. The stroke at + 40 °C yielded the same result as the blow at + 35 °C and + 33 °C: the crack was already arrested in the HAZ; there was only a shear zone behind the HAZ, Fig. 15. At + 30 °C the energy of 255 kpm was absorbed but the crack had already propagated halfway of the cross section, Fig. 16, and the second stroke caused the complete rupture of the specimen. Once more, the fracture face was mainly of cleavage nature - there seems to be no distinct difference to the characteristic formed at ± 0 °C. When determining the DWT temperature by using the full wall thickness and only ductile behaviour (no cleavage), a good correlation is given with the temperature that yields the first transition from cleavage to dimples in the Robertson test. This criterion cannot be defined by only bending the DWT-specimen as per ASTM; the specimen has to be deformed to such a degree as to overcome the (tougher) HAZ. Accordingly, a brittle fracture safe temperature would be that temperature, where in the non-affected base material no crystalline fracture face appears.

4. Notched Bar Impact Bending Test

The Charpy-V-notched impact strength, determined with specimens of the same 22 NiMoCr 37 plate as the Robertson specimen, yielded the temperature pattern of Fig. 17. In accordance with the Robertson test and DWT the upper level is + 35 °C approx. With decreasing temperature the values decline and at - 100 °C the lower level is reached. In the transition zone fracture faces always show crystalline spots.

The boundary value of $a_K = 8,7 \text{ kp/cm}^2$ (40 ft lb.), given by ASME PVC III, App. G (1972), yields a temperature of - 40 °C approx., the lateral expansion of 0,9 mm (35 mils) yielding - 50 °C. Both temperatures are used to control the NDT-value and may only exceed the same by 35 °C otherwise the NDT temperature must be corrected adequately. The example in question does meet this requirement, as $T_{\text{Ch-V}} - 33 \text{ °C} = - 40 - 33 = - 73 \text{ °C}$ is below $T_{\text{NDT}} - 30 \text{ °C}$. This example indicates on the other hand that there exists no direct correlation between the boundary value of $8,7 \text{ kpm/cm}^2$ and either the NDT-temperature or the ductile fracture range.

5. Evaluation of Testing Methods

All three test methods allow to determine the temperature where the fracture characteristic - at a certain wallthickness - transits from cleavage to ductile (dimple) fracture. Here a good correlation was observed between Robertson test and DWT. As for the notched impact bending test, at least that smaller specimen yields the same temperature, if the absolute

upper level without crystalline part is considered. In the case of the notched impact bending specimen the fracture is enforced by largescale deformation. An uncertainty is thus before all, how far the preceeding plastic deformation has influenced the formation of the cleavage fracture, and whether this could substitute the scale effect. The quantitative correlation in the discussed case might be random.

The influence of the wallthickness on the transition temperature in the Robertson test can be gathered from the fact, that the extension of the shear lips increases with rising temperature. That a premature crack arrest may occur, due to smaller wall thicknesses is intelligible as the resistance of both zones is of determinative influence for the balance against the outer force. In the case of St 37 the influence on wall thicknesses from 20 to 55 mm was small; papers [6] give WSB 70 values of -45°C for 12 mm and -15°C (-12°C) for 40 (120) mm wall thickness.

Apart from the scattering in the material it thus seems, as if from wall thicknesses exceeding 30 to 40 mm the fracture characteristic does not vary much. This does by no means signify, that the danger of brittle fracture is the same with all wall thicknesses, as the amount of cleavage does prevail more and more with increasing wall thicknesses.

An addition of 33°C on the T_{NDT} as per ASME/ASTM is definitely insufficient to avoid cleavage altogether; a safe temperature limit should rather be fixed as to eliminate cleavage with specimens of adequate thickness. In the case discussed this temperature was found to exceed the NDT-temperature by 65°C . That temperature exceeds the lower level of the notched impact strength by 30°C to 60°C .

ASME has now come to the same conclusions [7]: for wall thicknesses over 150 mm 66°C must be added to the NDT-temperature; contrary to this, for wall thicknesses of 25 mm an addition of 33°C is supposed sufficient. The described effects of the mixed fracture may have led to the conviction that the latter classification were justified.

The hitherto existing definition must thus be regarded to be more or less empirical. Transferring the results of the specimen to components may lead to misestimations. To throw more light on the interrelations further tests are under way [8].

Ductile fractures as shown in Fig. 5 for temperatures t 54 to t 61°C , only can be arrested, if the stress is decreasing below a certain critical (material dependent) value. For tests and failures this value is depending not only from the nominal membran stress but also from the superimposed secondary stresses. Therefore a reliable definition is very difficult. In this connection tests with rotating discs are running.

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Table 1: Material dates, conditions and results of Robertson tests

denomination	chem. composition										yield ult. point stress σ_Y σ_U kp/mm^2	elon- gation δ_5 %	con- traction ψ			
	C	Si	Mn	P	S	Cr	Cu	Al	Mo	Ni				N		
R St 37-2	.14	.21	.44	.023	.024	-	-	-	-	-	.004	26	41	71		
St 37-3	.12	.23	.60	.015	.024	-	-	.031	-	-	.005	27	42	73		
22 NiMoCr 37	.17	.29	.69	.009	.009	.395	.11	.021	.65	.783	-	48	62	64		
speci- men	material	wall- thckn. mm	test	grip		crack-length mm		temperature °C for shift to shear		nom. stress σ_n kp/mm^2 before 1) after 1) blow						
1	R St 37-2	20	gra- dient	short		230		+ 9		+ 9		15,6				
2														280		+ 20
3			(400) 2)			+ 23		+ 23		15,7						
4												202		-		-
5						358		-		-						
6												190		+ 28		+ 10
7	St 37-3	55	grad.	long		198		+ 11		+ 17						
8	R St 37-2	20	grad.									(400)		-		+ 9
9						iso- therm			136		-					
10			grad,										201		n.b. 3)	
11						St 37-3			55			(400)				
12	114													-		+ 31
13						208 4)			+ 34/54 4)		+ 61		25			
14	(400)														+ 28,5	
15																

1) without bending

2) through crack

3) not defined

4) see Fig.5

1) without bending 2) through crack 3) not defined 4) see Fig.5

Table 2: Results of modified Drop-Weight-Tests

spec.	temperature °C	energy kpm	limited bend mm	result
1	+ 30	122	1,5	no crack
		143	+ 0,4 = 1,9	crack in brittle bead
	- 10	143	+ 1,9 = 3,8	fracture
2	+ 10	143	1,9	crack arrested in HAZ
	0		+ 1,9 = 3,8	crack 5 mm in base material
3	0	143	1,9	crack 6 mm in base material
unlimited				
4	+ 40	180 200	10	crack arrested in HAZ
	+ 35	255		
5	+ 30	220		crack fracture
		255		
6	+ 35	275	7	as 4
	+ 33	275

Fig. 1: Dimensions of the Robertson specimen

Fig. 2: 1 000 Mp-device with long grips and blow-hammer

Fig. 3: Fracture surface of Robertson specimen 8

Fig. 4: Robertson spec. 14 with crack

Fig. 5: Fracture surface of Robertson specimen 14

Fig. 6: Fracture surface REM of spec. 14 (C, Fig. 5)

Fig. 7: Detail of Fig. 6

Fig. 8: Dimpled fracture (D, Fig. 5)

Fig. 10: Detail 1 of Fig. 9

Fig. 11: Detail 2 of Fig. 9

Fig. 9: Cut A of Fig. 5

Fig. 12: Relation between DWT - LEFM, schematic
left: load-deflection: (0) without crack
(1) small crack
(2) large crack
right: load-COD for same cases

Fig. 13: Fracture surface of DWT-spec.
1 ($30^{\circ}\text{C}/-10^{\circ}\text{C}$)

Fig. 14: Fracture surface of DWT-spec.
1 ($+10^{\circ}\text{C}/0^{\circ}\text{C}$)

Fig. 15: Fracture surface of DWT-spec.
6 ($+40^{\circ}\text{C}/35^{\circ}\text{C}$)

Fig. 16: Fracture surface of DWT-spec.
5 ($+30^{\circ}\text{C}$)

Fig. 17: Ch-V-impact-strength and lateral expansion in relation to temperature (A 508).