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DVGW Project SyWeSt H2: “Investigation of Steel Materials for Gas Pipelines and Plants for Assessment of their Suitability with Hydrogen”

Final Report

Dr. Michael Steiner
Open Grid Europe GmbH, Essen
Dr. Ulrich Marewski
Open Grid Europe GmbH, Essen
Dr. Horst Silcher
MPA, University of Stuttgart

DVGW Innovationsprogramm H2

MPA

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DVGW Project SyWeSt H2: “Investigation of Steel Materials for Gas Pipelines and Plants for Assessment of their Suitability with Hydrogen”

Final Report

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Summary

In connection with the construction of new high-pressure gas pipelines or their conversion, the suitability of the materials used within the context of complex fracture-mechanical investigations has to be evidenced in line with the DVGW Code of Practice, depending on pipeline design and the materials used. In order to simplify this currently necessary process, the DVGW initiated the SyWeSt H2 research project whose objective was to investigate the fracture-mechanical material behaviour of the steel grades in use.

As part of this project, fracture-mechanical tests were performed on a representative cross-section of typical pipeline steel grades used in Germany (and, in some cases, elsewhere in Europe). With respect to all tested pipeline steel grades, the investigations demonstrated their suitability for hydrogen transmission since both the stipulated minimum fracture toughness was adhered to and crack growth behaviour corresponded to the expected values.

In comparison to ASME B 31.12, it was possible to extend the scope of application with regard to the description of crack growth. This particularly relates to the additional introduction of the influence of both mean stress and hydrogen pressure on crack growth.

Due to the established relatively low-level scatter for crack growth in materials of a different strength and a very different age, it can be concluded that comparable materials which were not tested in this project are covered by the test results. Thus, the intended objective of the SyWeSt H2 research project was achieved for the group of pipeline steel grades and the pipeline steel grades used in plants.

Because the test programme necessarily focussed on steel grades used in pipelines and plants, only a few materials which are normally used for valve housings could be tested. These tests also predominantly demonstrated the suitability of the materials involved for use with hydrogen. Since the range and possible microstructures of these frequently cast materials could, however, not be covered by the research project by a long way, it is recommended to perform further tests, at least for this group of materials.

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1 Terms of Reference

For hydrogen transmission within the German gas grid, it is imperative to obtain a clearly defined assessment of steel components for hydrogen suitability and relevant implementation in the DVGW Codes of Practice. Within this context, DVGW Code of Practice G 409 [1] (for the conversion of pipelines to hydrogen transmission) and DVGW Code of Practice G 463 [2] (for the construction of new pipelines), for example, have been specifically aligned to hydrogen as a transmission medium. Both these codes of practice may require a fracture-mechanical assessment of pipelines and pipeline components, with fracture-mechanical parameters being required as input variables.

So far, it was only in ASME B 31.12 [3] that these parameters were specified in an international code of practice. They specifically involve minimum fracture toughness (K_{Ic}) and the description of crack toughness (da/dN) with hydrogen as a medium. However, the parameters specified in ASME B 31.12 were based on investigations on US materials which are very similar, but not identical, to the materials used in Germany and elsewhere in Europe. Furthermore, the conversion of existing older natural gas pipelines (comprising older materials) is of very considerable interest particularly for the scope of application of the DVGW Code of Practice, although a direct transferability of the US investigations was considered to be problematic.

Hence, within the context of the DVGW's extensive SyWeSt H2 research project, fracture-mechanical investigations were performed specifically for the pipeline steel grades used in Germany (and, in some cases, elsewhere in Europe) with hydrogen as a medium. The objective of this project was to compare the established fracture-mechanical parameters with the results on which ASME B 31.12 is based for the purpose of validating their application to steel grades used in Germany and, where applicable, drawing up a modified correlation for crack growth.

2 Basic Procedure for Performance of Fracture-Mechanical Tests

The material to be investigated was obtained from high-pressure gas pipeline sections featuring different pipe diameters and wall thicknesses, focussing not only on the base material but also on the weld areas (longitudinal welds, spiral welds, on-site girth welds (Figure 2.1).

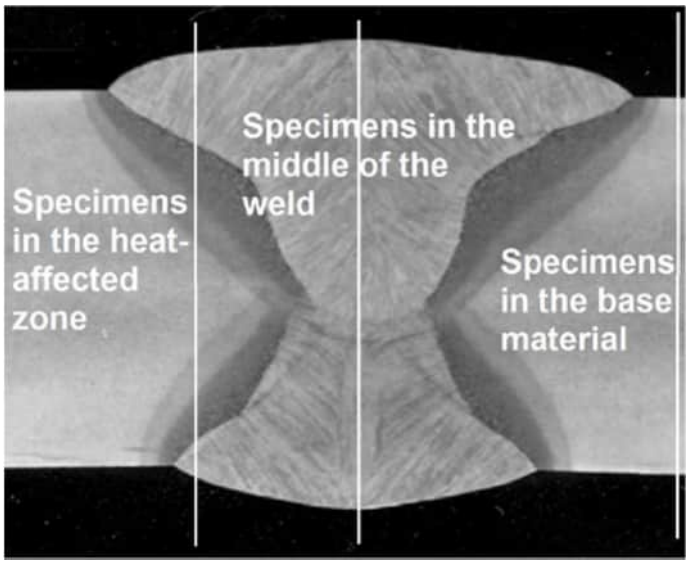


Figure 2.1: Cross-section of a submerged arc-welded steel pipe

Due to the different pipe geometries of gas transmission pipelines, the sample size for fracture-mechanical testing is in some cases restricted. Because of the, in some cases, thin walls, the standard samples were so small that they were no longer capable of being tested from a technical point of view and the validity of the test results was limited. For reasons of comparability, the dimensions of the samples from different pipes are to be similar. Hence, a sample form corresponding to the contour of a C(T)20 sample was selected (Figure 2.2). As a rule, a sample thickness of 10 mm was used wherever possible. This sample thickness was reduced in some cases (e.g. in the case of an excessively thin wall).

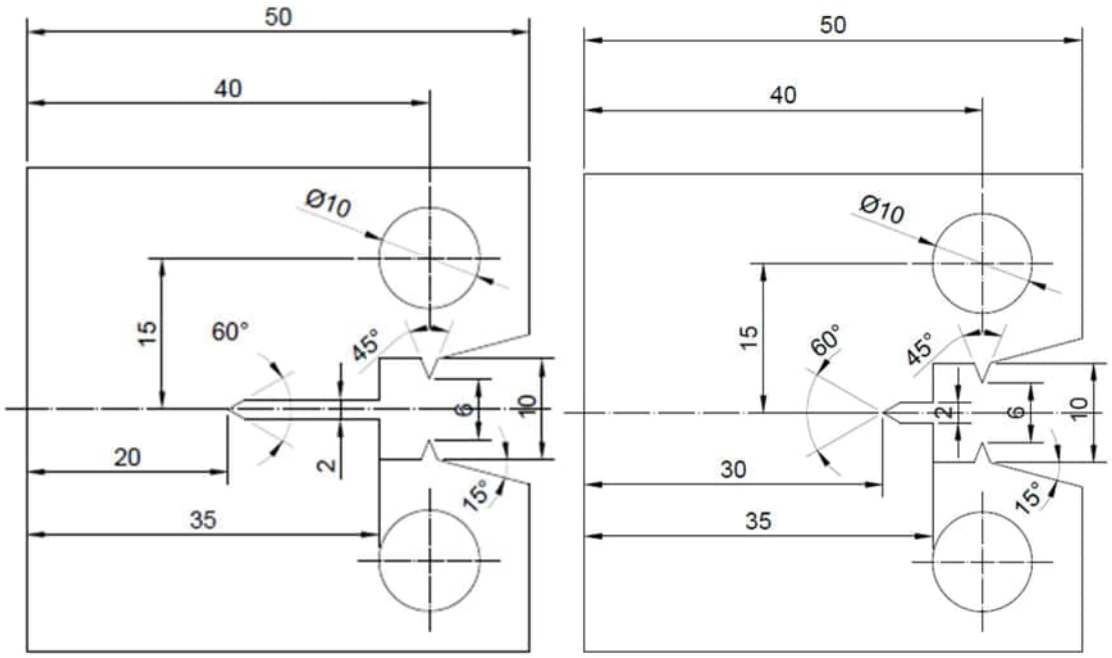


Figure 2.2: Sample geometry for static tests (left) and cyclical tests (right)

The samples were marked on the pipe and sawn out and a blank was then milled. On weld joints, the front faces were also ground and slightly etched in order to make the weld visible. The notch plane was then defined on the marking table so as to serve as a reference plane for production. The bolt holes and the notch contour of the samples were cut out by means of the wire-eroding method.

Figure 2.3: Removal of samples from a spiral welded pipe

Prior to testing, an approx. 2 mm fatigue crack has to be made on the samples. The conditions applicable for subjecting the samples to cyclical load are specified in ASTM E1820-20 [4]. The maximum load when subjected to cyclical load has to be less than the load at the beginning of the actual test. The samples for the cyclical tests have an initial crack depth ratio of approx. 0.3. In the static crack resistance curve tests, this ratio is about 0.5. After being subjected to cyclical load, the C(T) samples of the static tests were 20% side-notched at the crack tip on the crack plane in order to increase the multiaxiality of the stress condition.

2.1 Test Set-up for Performance of Fracture-Mechanical Tests in Hydrogen Atmosphere

In order to establish the impact of hydrogen, the samples had to be exposed to a pressurised hydrogen atmosphere during testing.

The hydrogen atmosphere was provided in autoclaves which enabled the load to be applied to the sample by way of a suitably sealed piston operation (Figure 2.4).

Figure 2.4: Servohydraulic testing system of MPA Stuttgart using an integrated hydrogen autoclave

Prior to testing, the sample was clamped in the autoclave whose lid was then closed. The necessary level of gas purity was obtained by flushing the sample with hydrogen several times. The hydrogen was then added at the pressure intended for test purposes. The autoclave is provided with thermal elements and a clip gauge for the purpose of monitoring the test parameters. The level of force applied is measured by a load cell installed outside the autoclave.

2.2 Cyclical Tests: Testing and Evaluation as per ASME E647 [5]

The test load ΔF was calculated from the load ΔK applied at the beginning of the test and from the ratio K_{min}/K_{max} (R ratio). Testing was performed load-controlled at a specified frequency. Due to crack growth Δa, cyclical stress intensity ΔK increases at a constant load range ΔF (Figure 2.5).

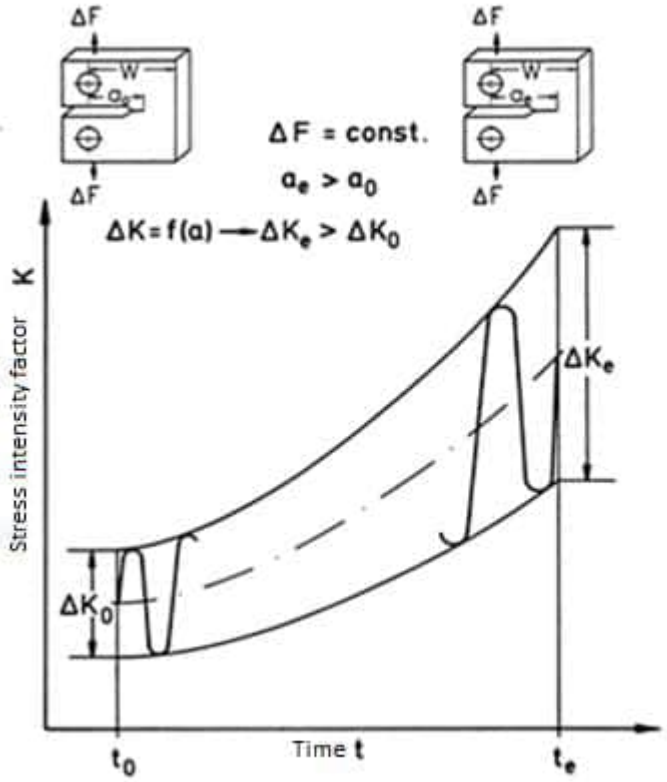


Figure 2.5: Increase in cyclical stress intensity ΔK due to crack growth

Testing was terminated and the sample removed at the specified end of the test (achievement of a certain ΔK value, a certain crack growth Δa or fracturing of the sample). The sample was deep-cooled in liquid nitrogen in order to expose the fractured surface and then, when brittle, broken up without deformation. Both the initial and final crack depths were measured on the fractured surface. During testing, the upper load and the lower load were measured using a load cell and a clip gauge was used to measure crack opening displacement (COD). The value pairs F_{max}-COD_{max} and F_{min}-COD_{min} result in a straight line which corresponds to the momentary rigidity of the sample. Crack growth causes rigidity to change, i.e. crack opening displacement increases at constant loads. The current crack depth can be calculated from the rigidity (Figure 2.6).

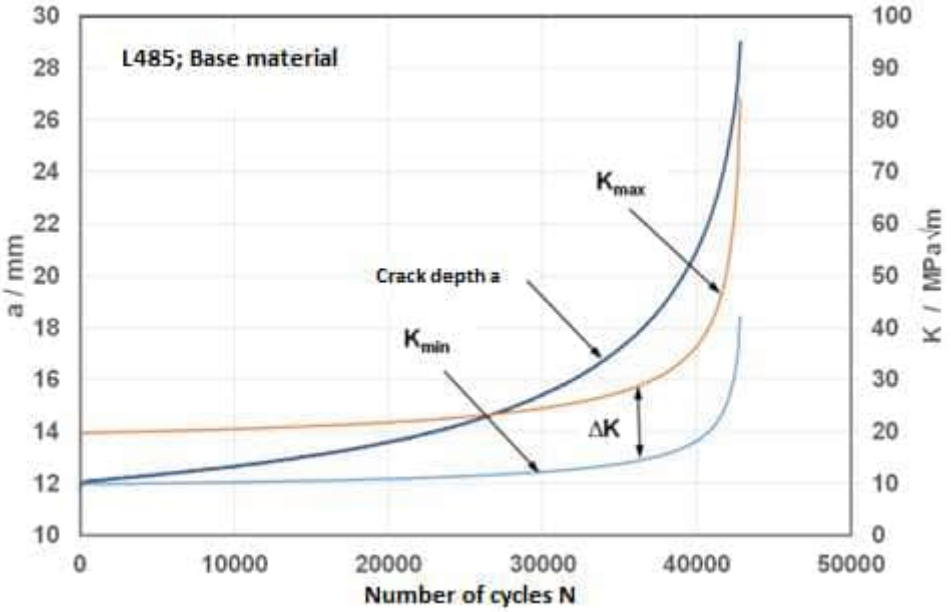


Figure 2.6: Crack depth and stress intensities K_{min}, K_{max} and ΔK depending on the number of cycles during testing

The correlation between crack depth and rigidity is calibrated using the initial crack depth and the initial rigidity. This correlation is checked on the basis of the final crack depth and the final rigidity and the crack growth values are adjusted as appropriate.

The area of the crack growth curve shown as a straight line in the double-logarithmic representation (Figure 2.7: area 2) can be approximated by the so-called Paris equation:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot \Delta K^m$$

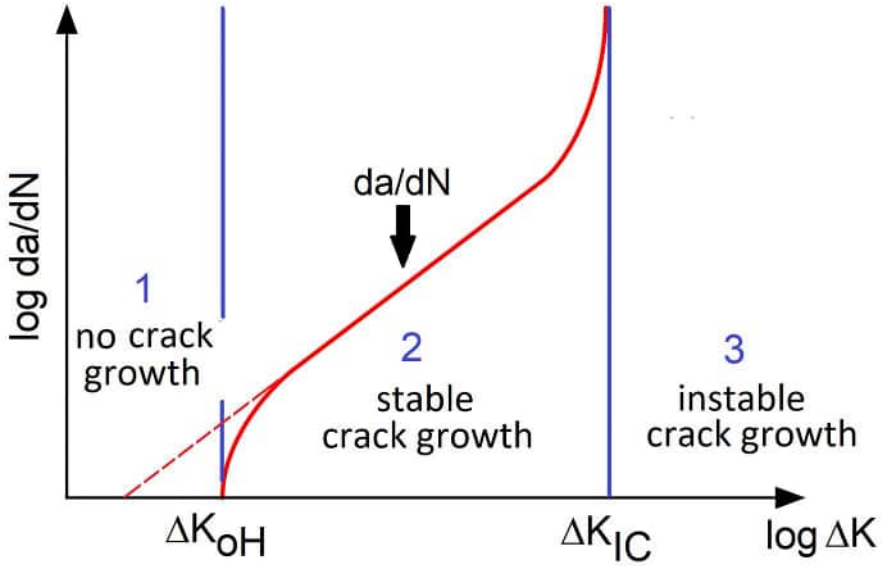


Figure 2.7: Schematic representation of crack growth depending on cyclical stress intensity ΔK

Parameters C and m are referred to as Paris parameters. At lower ΔK values, the crack growth rates decrease more considerably (area 1) until any measurable crack growth no longer occurs. The relevant ΔK value is designated as a threshold value. At higher ΔK values, the crack growth rate increases considerably (area 3). Due to increasing (alternating) plastification,

the sample in each cycle is subjected to over-elastic deformation until the crack has grown to such an extent that the force F_{max} is sufficient to rupture the sample.

2.3 Static Fracture-Mechanical Testing: Testing and Evaluation as per ASTM E1820

The sample for static fracture-mechanical testing was subjected to a load in a strain-controlled condition, i.e. a certain increase in notch opening per time unit was specified. The test machine provided the relevant necessary load. Consequently, the sample can continue to be subjected to stable testing, even after exceeding the maximum load. Continued load application was stopped at defined intervals and the currently applied load was reduced by 20%. Testing was then continued until the next reduction in load (Figure 2.8).

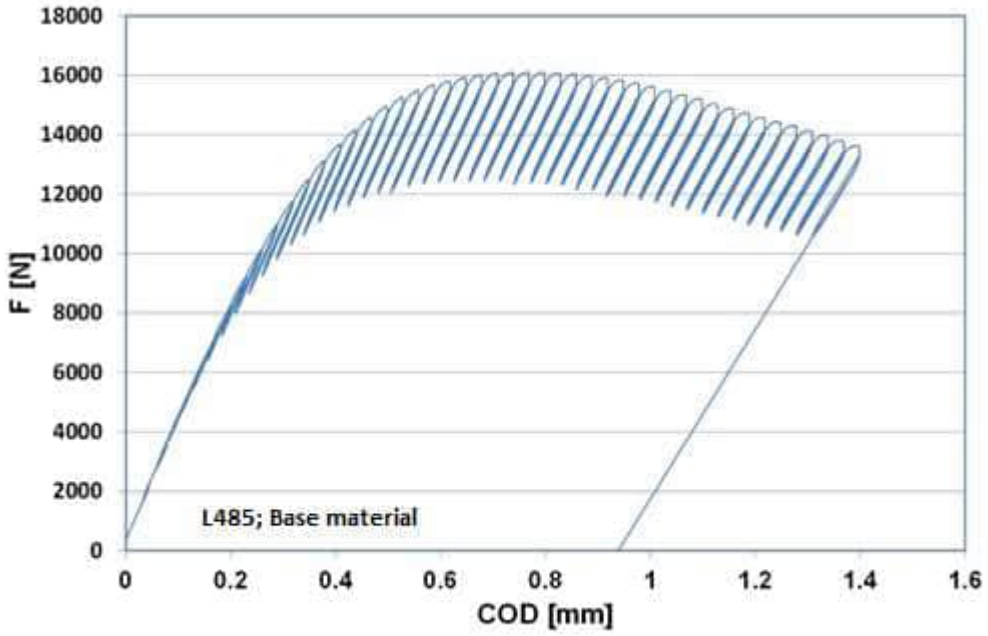


Figure 2.8: Load-crack opening diagram (F-COD)

During testing, the sample was subjected to increasing plastic deformation at the crack tip. At the same time, crack growth increased, causing the sample's load capacity to decrease. If the crack has increased sufficiently without the sample being fractured beforehand, the load applied to the sample is removed and the test is terminated. During testing, the load (F) and crack opening displacement are measured.

The area below the F-COD curve represents the deformation energy absorbed by the sample, from which the J integral is calculated. The load reduction steps are used to calculate the sample's rigidity at different stages of the test. As is the case with the cyclical tests, crack growth is calculated from the changes in rigidity and is compared with the initial and final values subsequently measured on the fractured surface. The combination of the J and Δa values from each load reduction step results in the J-Δa points. A curve of the shape

$$J = A \cdot \Delta a^b$$

is plotted through the valid points between the offset lines at a growth rate of 0.15 and 1.5 mm as an approximation. This curve involves the crack resistance curve or JR curve (Figure 2.9).

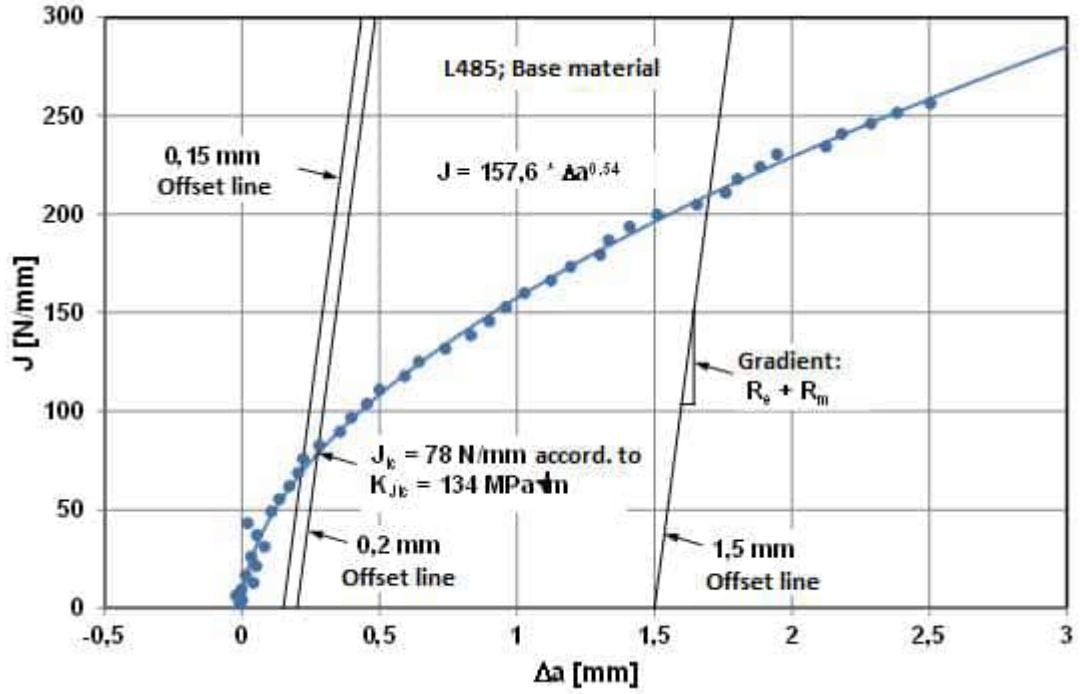


Figure 2.9: Crack resistance curve (JR curve)

Using this curve and the 0.2 mm offset line, the fracture-mechanical parameter J_{Ic} is established as the point where the curve intersects with this offset line. This J_{Ic} value can be formally determined with E (modulus of elasticity ~210,000 MPa and μ~0.3 for steel) using the following formula:

$$K_{JIC} = \sqrt{\frac{E \cdot J_{Ic}}{1-\mu^2}}$$

In contrast to the K_{Ic} value, the K_{JIc} value is an elastic-plastic parameter which includes the deformation energy of the test.

3 Investigated Materials

By way of a summary, Figure 3.1 shows the investigated materials, the investigations performed and the main test parameters.

For this purpose, MPA Stuttgart was provided with several pipeline steel grades and some pipe steel grades used in existing plants. In addition, a few steel grades which are typically used in valve pressure vessels were also investigated. The test programme was implemented for the majority of samples at a constant hydrogen pressure of p_{H2} = 100 bar.

In order to check the impact of hydrogen pressure on the resulting fracture-mechanical properties, testing was also performed on selected materials at hydrogen pressures of p_{H2} < 100 bar.

In the currently valid ASME B 31.12, the scope of validity of the described crack growth equations is limited to R values of ≤ 0.5. For this reason, crack growth tests at R values of 0.1 and 0.7 were also performed for two selected materials (L360 and L485).

Since ASME B 31.12 describes additional limitations in terms of the maximum hardness of welds, the impact of different hardnesses on fracture-mechanical properties was also investigated on the material L485 as an example.

Material	Testing da/dN & K_{IC}	H_2 Test pressure [bar]	R-value
L290 NE	BM, SAWL		
Grade A	BM, SAWL		
St35	BM		
15 k (St.35)	BM, SAWL, GW		
X42	BM, ERW, GW, HAZ		
RR St 43.7	BM		
P355 NH	BM		
L360 NE	BM		
StE 360.7	SAWL, BM		
L360 NB	SAWL BM		
14 HGS	BM, LW, GW		
TStE 355 N	BM		
WSTE 420	BM		
St53.7	GW, BM		
X56.7	BM, SAWL, GW		
St60.7	BM, GW	100	0.5
P 460 NH	SAWL, BM		
X70	BM, SAWH, HAZ		
X70	BM, GW, HAZ		
L485	BM, SAWH, HAZ		
GRS550/X80	BM, SAWL		
L485 (HV high/low)	BM, GW, HAZ		
L415 (curve)	BM, SAWL		
P355 NL1 (Valve)	BM		
GJS 400 (Valve)	BM		
C22.3 (Valve)	BM		
GS C25 N (Valve)	BM		
P460 QL1 (Valve)	BM		
St35	BM	0 / 0.2 / 1 / 2 / 5 / 10 / 20 / 100	
L485	BM		
L360 NB	BM, WM	10 / 100	
StE 320.7	BM, GW		
StE 480.7 TM	BM, SAWL, GW		
L485	BM	100	0.1 / 0.5 / 0.7
L360	BM		

Legend	
da/dN	Crack growth
K_{IC}	Fracture toughness
BM	Base material
HAZ	Heat-affected zone
SAWL	Submerged arc longitudinal weld
SAWH	Submerged arc spiral weld
ERW	Electric Resistance Weld
GW	Girth weld
LW	Longitudinal weld
WM	Weld material

Figure 3.1: Investigated materials

The range of tested materials extends from St35 with relatively low strength, dating back to 1930, through to GRS550 (X80). Within the context of the availability of the test material, it was ensured that comparable, more recently and older manufactured materials were investigated as far as possible also in terms of strength comparison. Thus, for example, the yield strength and the tensile strength of both X70 and L485 are almost identical, whereas their ductility properties and, in particular, their notched-bar impact work values differ considerably.

The sample material is thus selected in line with the approach described in [6] (Figure 3.2), according to which the materials used in pipeline construction can be categorised into material classes.

Material [2]			
StE 210	St 34/35		Grade A
StE 240	St 37/38	L245	Grade B
StE 290	St 42/43	L290	X42
StE 320	St 47		X46
StE 360	St 52/53	L360	X52
StE 385	St 56		X56
StE 415	St 60	L415	X60
StE 445		L450	X65
StE 480	St 70	L485	X70
GRS 550		L555	X80

[2] Other materials are to be assigned accordingly.

Figure 3.2: Material classes in pipeline construction

The following pages show the characteristics (where available) of each investigated steel grade: year of construction, production standard, specific minimum characteristics and measured characteristics, chemical composition, and tested fracture toughness. The crack growth in the investigated steel grade is then shown. In addition, hardness measurements were performed for selected steel grades. Depending on the material involved, the base material, the weld material and the heat-affected zone were tested. All measured values related to a Vickers hardness measurement with HV10.

3.1 L290 NE

The samples were taken from a longitudinally submerged arc-welded pipe with a diameter of 711 mm and a wall thickness of 12.5 mm.

The base material features the following data:

Table 3.1: Characteristics for L290 NE

Production year	2020	
Production standard	ISO 3183 (2018-09)	
Specific minimum characteristics	R_e [MPa]	290
	R_m [MPa]	415
	K_v[1] [J]	40
Material characteristics	R_e [MPa]	422
	R_m [MPa]	560
	K_v [1] [J]	158

Table 3.2: Chemical composition of L290 NE

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.15	0.2	1.57	0.02	0.002	0.15	0.15	0.05
	Ni	V	Ti	Nb				
	0.15	0.01	0.017	0.02				

Table 3.3: Fracture toughness of L290 NE

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
L290 NE	Base material	39	153.4
L290 NE	Weld material of longitudinal weld	39	156.4

The curves describing crack growth in fatigue testing in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material (BM)
- weld material of the longitudinal weld (WM-LW)

[1] Transverse notched-bar impact =90°; V-sample as per DIN EN ISO 148-1 at -20 °C

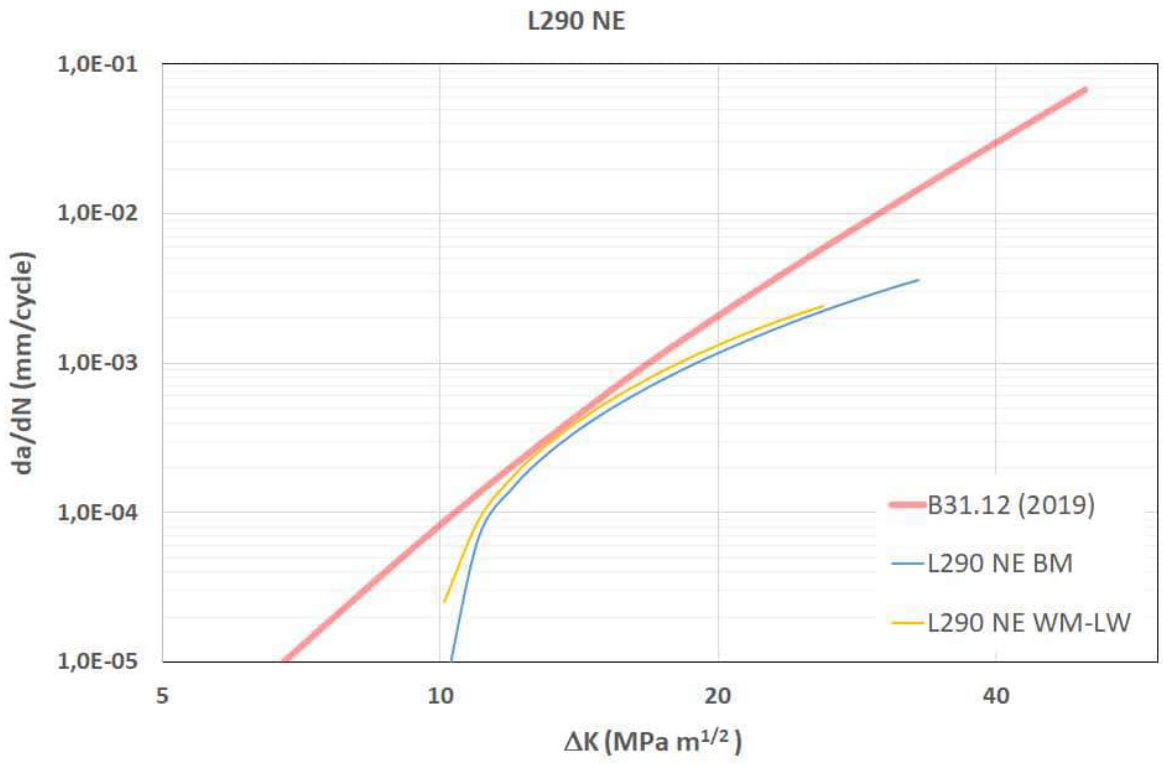


Figure 3.3: Crack growth L290 NE

Hardness measurements were performed on two metallographic samples from item no. 39. The results of these hardness measurements are shown in Figures 3.4 to 3.9.

MPA STUTTGART

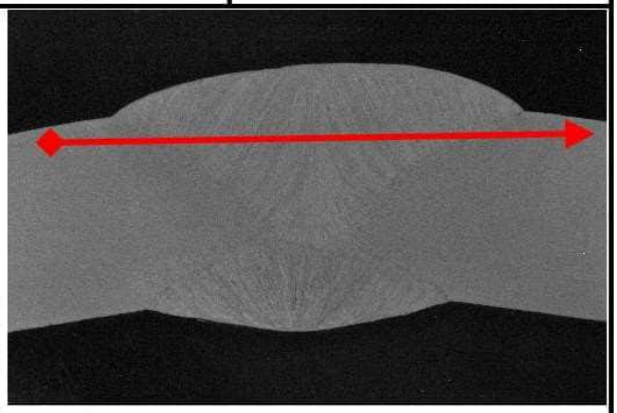
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und
Elektronenmikroskopie

Order number	9039784000
Sample description	39.1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation No.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	317,6	314,5	0,3160	186	181		BM 1
2	316,3	316,1	0,3162	185			
3	318,8	317,0	0,3179	184			
4	321,7	323,0	0,3223	178			
5	328,8	328,4	0,3286	172			
1	320,3	320,9	0,3206	180	188		HAZ 1
2	315,3	314,2	0,3148	187			
3	311,6	310,3	0,3109	192			
4	313,0	308,0	0,3105	192			
5	316,5	313,2	0,3149	187			
1	292,0	291,8	0,2919	218	202		WM
2	304,1	303,5	0,3038	201			
3	310,1	308,4	0,3093	194			
4	306,4	307,0	0,3067	197			
5	302,0	303,7	0,3028	202			
1	304,5	304,3	0,3044	200	193		HAZ 2
2	301,2	303,5	0,3023	203			
3	312,2	312,2	0,3122	190			
4	315,5	316,3	0,3159	186			
5	315,3	315,3	0,3153	187			
1	331,3	331,9	0,3316	169	176		BM 2
2	326,1	325,5	0,3258	175			
3	322,6	323,8	0,3232	178			
4	321,9	324,0	0,3230	178			
5	320,7	319,0	0,3199	181			

Date: 06.11.22

Tester: Scheck

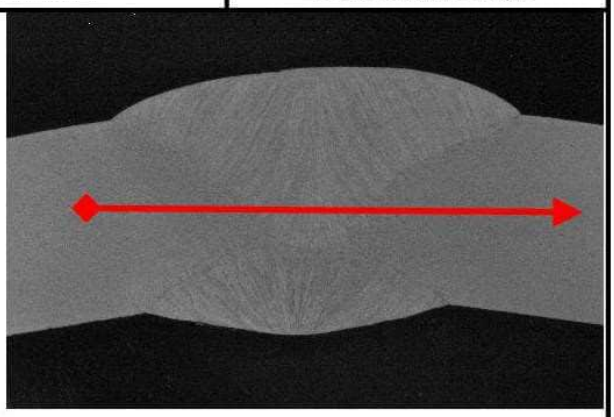
Figure 3.4: Hardness measurements of L290 NE (1)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und
Elektronenmikroskopie

Order number	9039784000
Sample description	39.1; Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	324,8	326,5	0,3257	175	174		BM 1
2	325,9	326,7	0,3263	174			
3	326,9	326,3	0,3266	174			
4	324,4	327,3	0,3259	175			
5	325,7	329,6	0,3276	173			
1	321,1	327,9	0,3245	176	179		HAZ 1
2	321,1	317,6	0,3193	182			
3	320,3	319,4	0,3199	181			
4	320,5	320,9	0,3207	180			
5	323,6	322,8	0,3232	178			
1	316,1	316,9	0,3165	185	181		BM
2	320,3	319,7	0,3200	181			
3	318,8	319,9	0,3193	182			
4	323,4	321,5	0,3224	178			
5	325,0	322,3	0,3237	177			
1	323,8	326,3	0,3251	176	175		HAZ 2
2	330,0	330,0	0,3300	170			
3	321,9	321,5	0,3217	179			
4	324,2	323,4	0,3238	177			
5	325,5	325,5	0,3255	175			
1	340,6	339,6	0,3401	160	166		BM 2
2	339,8	342,9	0,3413	159			
3	332,5	334,6	0,3336	167			
4	328,4	329,4	0,3289	171			
5	327,9	330,6	0,3293	171			

Date: 06.11.22

Tester: Scheck

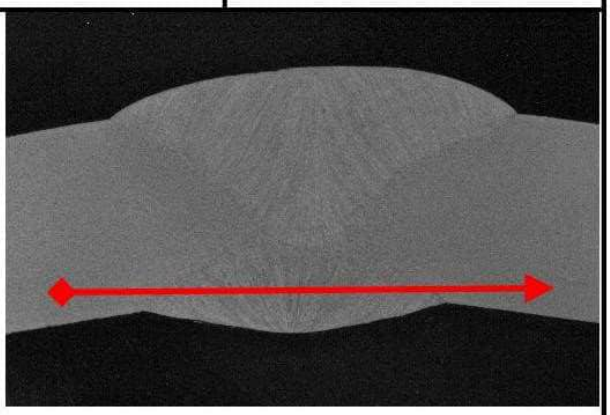
Figure 3.5: Hardness measurements of L290 NE (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und
Elektronenmikroskopie

Order number	9039784000
Sample description	39.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	323,8	329,8	0,3268	174	165		BM 1
2	336,3	337,7	0,3370	163			
3	335,2	335,8	0,3355	165			
4	334,6	333,3	0,3340	166			
5	341,6	341,0	0,3413	159			
1	332,5	333,3	0,3329	167	173		HAZ 1
2	324,0	324,4	0,3242	176			
3	328,0	326,5	0,3272	173			
4	329,4	330,6	0,3300	170			
5	324,6	321,5	0,3231	178			
1	322,6	323,6	0,3231	178	175		WM
2	324,4	325,2	0,3248	176			
3	328,4	324,8	0,3266	174			
4	326,7	326,3	0,3265	174			
5	326,9	324,0	0,3255	175			
1	336,0	332,7	0,3344	166	165		HAZ 2
2	329,6	336,5	0,3330	167			
3	335,0	332,7	0,3339	166			
4	333,1	333,3	0,3332	167			
5	342,5	343,1	0,3428	158			
1	341,9	343,7	0,3428	158	162		BM 2
2	340,6	340,6	0,3406	160			
3	338,7	338,9	0,3388	162			
4	337,9	339,0	0,3384	162			
5	329,6	333,3	0,3315	169			

Date: 06.11.22

Tester: Scheck

Figure 3.6: Hardness measurements of L290 NE (3)

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Hardness test

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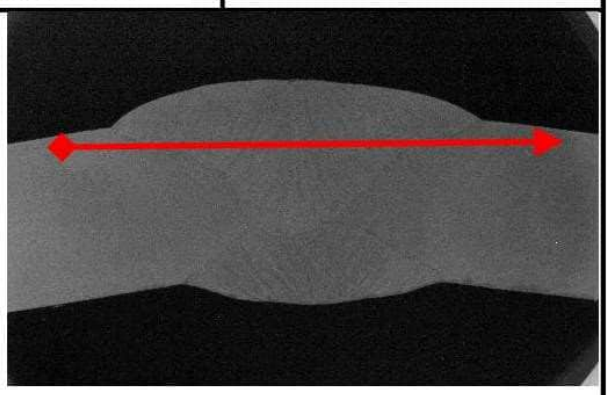

Order number	9039784000
Sample description	39.2; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	315,5	316,3	0,3159	186	186		BM 1
2	314,0	315,1	0,3146	187			
3	314,0	315,1	0,3146	187			
4	315,7	317,4	0,3165	185			
5	319,2	318,4	0,3188	182			
1	306,8	309,7	0,3082	195	194		HAZ 1
2	305,1	305,7	0,3054	199			
3	311,1	312,4	0,3118	191			
4	312,2	311,8	0,3120	191			
5	310,9	310,5	0,3107	192			
1	299,9	301,4	0,3007	205	199		WM
2	305,5	303,9	0,3047	200			
3	309,1	306,6	0,3078	196			
4	305,3	307,4	0,3064	198			
5	309,5	306,2	0,3078	196			
1	316,3	317,6	0,3170	185	188		HAZ 2
2	316,3	315,1	0,3157	186			
3	313,6	314,0	0,3138	188			
4	312,4	313,6	0,3130	189			
5	312,4	309,9	0,3111	192			
1	336,1	335,8	0,3359	164	175		BM 2
2	329,6	328,8	0,3292	171			
3	326,5	324,4	0,3255	175			
4	323,6	324,0	0,3238	177			
5	315,9	315,7	0,3158	186			

Date: 06.11.22

Tester: Scheck

Figure 3.7: Hardness measurements of L290 NE (4)

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Test report
MPAS-PPB 52310-08/1
Hardness test

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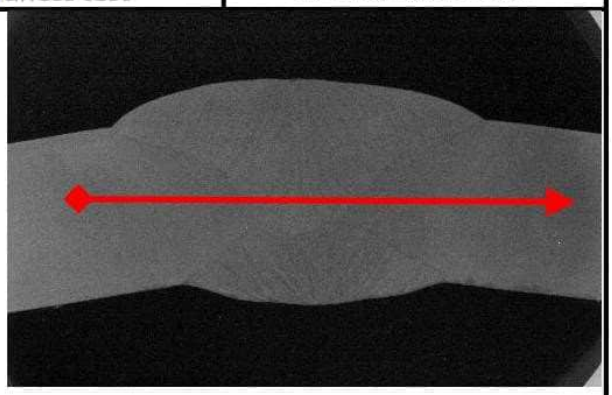
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	39.2; Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	321,5	325,0	0,3233	177	176		BM 1
2	321,7	324,0	0,3229	178			
3	327,3	324,2	0,3258	175			
4	322,8	323,4	0,3231	178			
5	325,9	327,1	0,3265	174			
1	318,8	321,7	0,3203	181	179		HAZ 1
2	319,9	319,9	0,3199	181			
3	321,3	320,9	0,3211	180			
4	323,0	319,4	0,3212	180			
5	324,6	326,9	0,3258	175			
1	316,5	315,1	0,3158	186	183		WM
2	318,4	315,3	0,3169	185			
3	317,2	316,1	0,3166	185			
4	322,3	321,5	0,3219	179			
5	322,8	320,1	0,3214	180			
1	320,7	320,7	0,3207	180	180		HAZ 2
2	320,9	319,0	0,3200	181			
3	321,3	323,6	0,3224	178			
4	319,4	319,9	0,3196	181			
5	320,3	319,9	0,3201	181			
1	341,0	341,2	0,3411	159	172		BM 2
2	330,2	332,9	0,3316	169			
3	326,1	324,8	0,3255	175			
4	321,7	322,8	0,3222	179			
5	322,5	325,5	0,3240	177			

Date: 06.11.22

Tester: Scheck

Figure 3.8: Hardness measurements of L290 NE (5)

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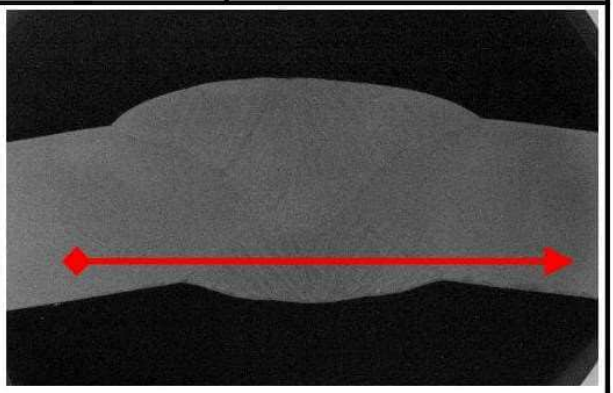
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	39.2; Root
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	334,2	335,0	0,3346	166	163		BM 1
2	336,9	338,9	0,3379	162			
3	331,5	334,4	0,3329	167			
4	340,6	341,0	0,3408	160			
5	340,2	340,2	0,3402	160			
1	335,2	333,8	0,3345	166	171		HAZ 1
2	331,3	329,4	0,3303	170			
3	331,9	331,3	0,3316	169			
4	327,5	327,5	0,3275	173			
5	326,1	323,4	0,3247	176			
1	328,0	326,5	0,3272	173	174		WM
2	327,8	327,9	0,3278	173			
3	329,8	326,1	0,3279	172			
4	325,7	324,4	0,3250	176			
5	325,3	323,8	0,3245	176			
1	323,2	321,7	0,3224	178	176		HAZ 2
2	323,6	323,4	0,3235	177			
3	325,5	327,1	0,3263	174			
4	327,1	329,0	0,3281	172			
5	324,0	324,6	0,3243	176			
1	339,6	338,5	0,3391	161	166		BM 2
2	337,7	336,7	0,3372	163			
3	331,9	330,9	0,3314	169			
4	333,3	334,2	0,3338	166			
5	330,4	331,3	0,3309	169			

Date: 06.11.22

Tester: Scheck

Figure 3.9: Hardness measurements of L290 NE (6)

3.2 5L Grade A

The samples were taken from a seamless hot-rolled pipe with a diameter of 406.4 mm and a wall thickness of 10 mm and a pipe bend with a wall thickness of 13 mm.

The relevant material-specific data is as follows:

Table 3.4: Characteristics of 5L Grade A

Production year	1962	
Production standard	API-STD 5L	
Specific minimum characteristics	R_e [MPa]	207
	R_m [MPa]	331
	K_v [J]	No requirements
Material characteristics	R_e [MPa]	297
	R_m [MPa]	422
	K_v [J]	17

Table 3.5: Chemical composition of 5L Grade A

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.15	0.14	0.57	0.017	0.02			
	Ni	V	Ti	Nb				

Table 3.6: Fracture toughness of 5L Grade A

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
5L Grade A (pipe)	Base material	42	109.5
5L Grade A (bend)	Base material	42	107.4

The curves describing crack growth in fatigue testing in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the base material.

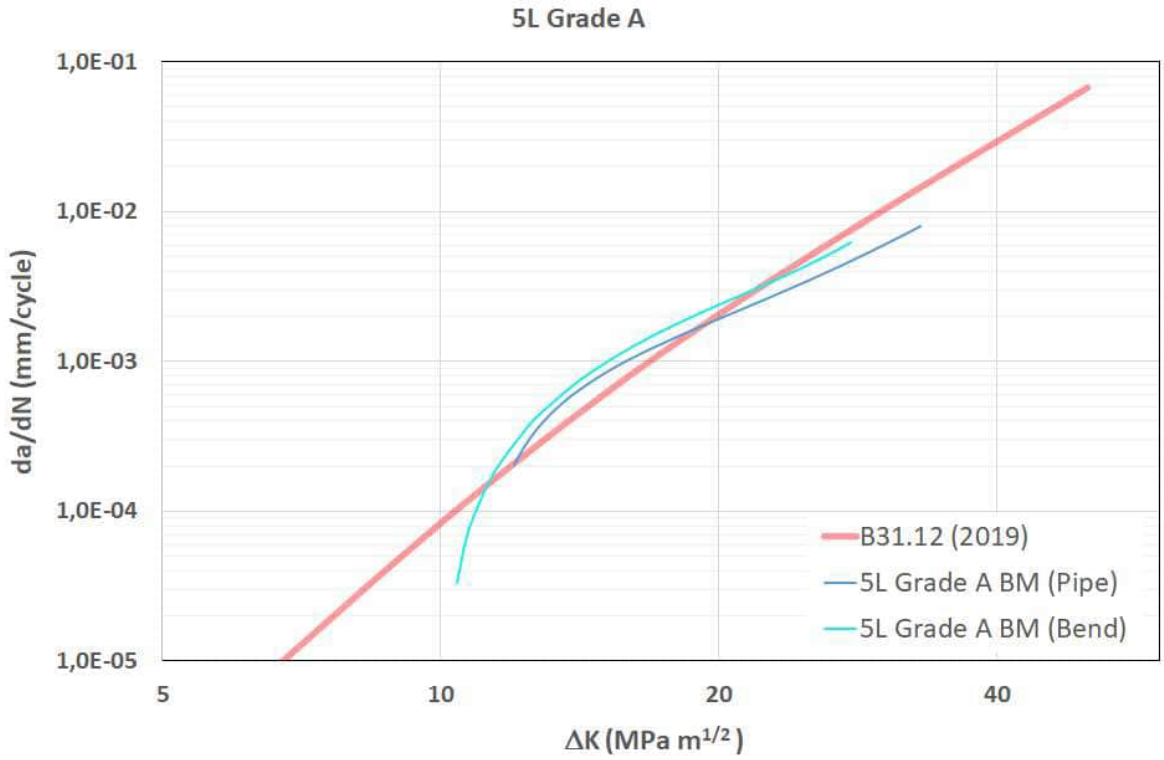


Figure 3.10: Crack growth 5L Grade A

3.3 St35

St35 from pipelines dating back to two different construction years was tested.

First, the results from a pipeline constructed in 1930 are shown. The samples were taken from a pipe with a diameter of 400 mm and a wall thickness of 10 mm.

The relevant material-specific data is as follows:

Table 3.7: Characteristics of St35

Production year	1930	
Production standard	DIN 1629	
Specific minimum characteristics	R_e [MPa]	235
	R_m [MPa]	350
	K_v [J]	No requirements
Material characteristics	R_e [MPa]	294
	R_m [MPa]	458
	K_v [2] [J]	10

Table 3.8: Chemical composition of St35

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.199	0.268	0.612	0.059	0.015	0.11	0.004	0.009
	Ni	V	Ti	Nb				
	0.017	0.001	0.002	0.001				

Table 3.9: Fracture toughness of St35

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
St35	Base material (100 bar)	1	101.9
St35	Base material (20 bar)	31	96.1
St35	Base material (10 bar)	30	100.8
St35	Base material (5 bar)	29	133.3
St35	Base material (2 bar)	28	135
St35	Base material (1 bar)	27	148.1
St35	Base material (0.2 bar)	26	147.3
St35	Base material (air)	25	170.5

For fatigue testing in a purely hydrogen atmosphere at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5, the samples were taken from the base material. The relevant crack growth curve is shown below.

[2] Notched-bar impact test as per DIN EN 10045; V-notch, circumferential direction

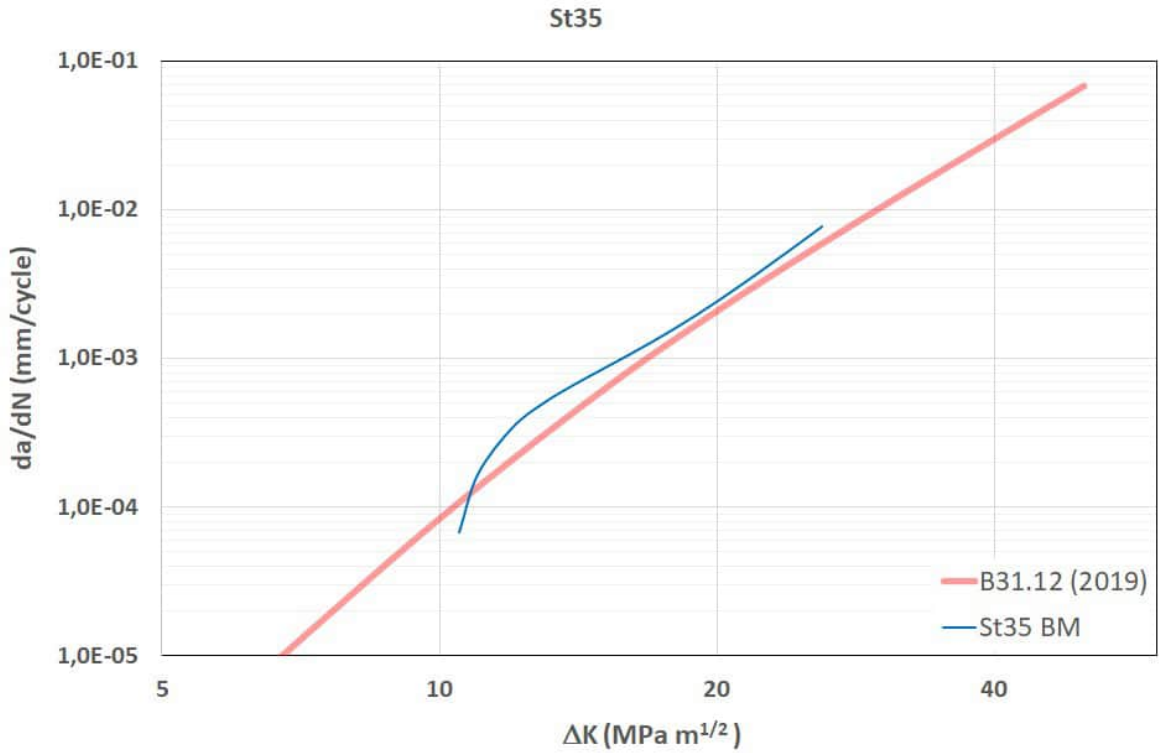


Figure 3.11: Crack growth St35

In addition, the material was investigated at different hydrogen pressures of 0 bar, 0.2 bar, 1 bar, 2 bar, 5 bar, 10 bar and 20 bar. The results of the crack growth measurements are shown below.

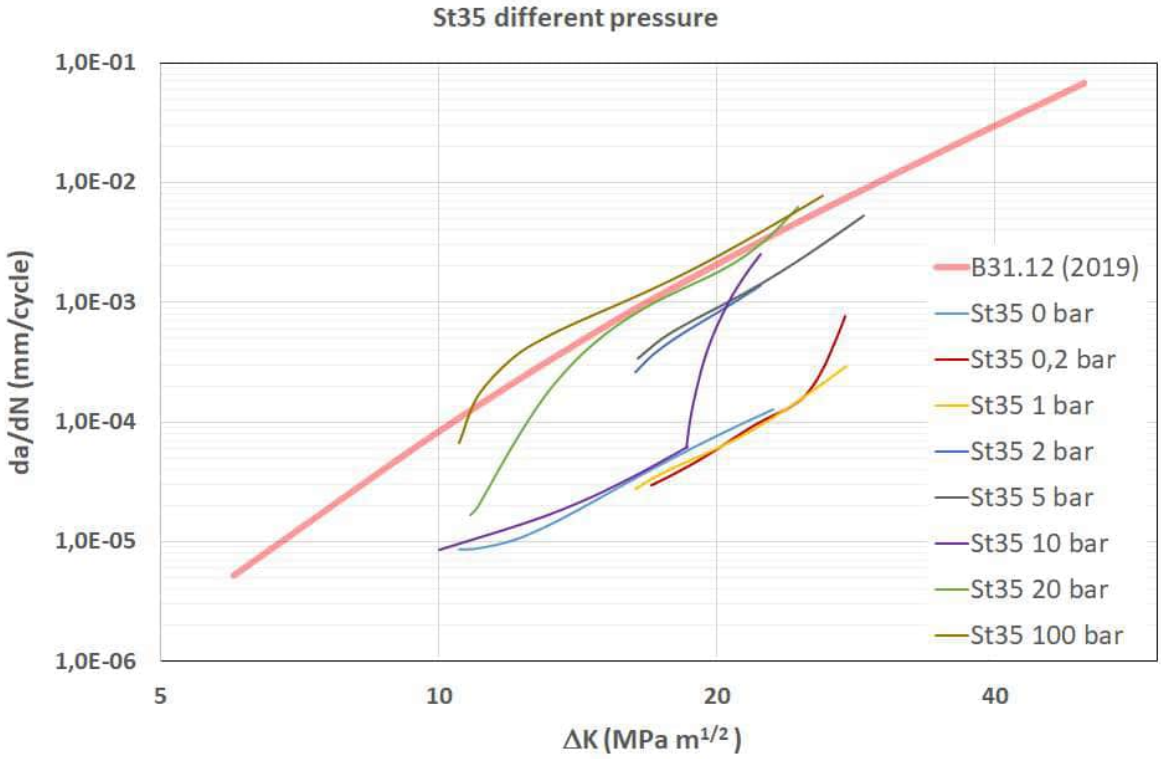


Figure 3.12: Crack growth St35 at different pressures

For St35, further samples were taken from pipes dating back to 1937. The results are shown below.

The samples were taken from a pipe with a diameter of 323 mm and a wall thickness of 7.75 mm.

The relevant material-specific data is as follows:

Table 3.10: Characteristics of St35

Production year	1937	
Production standard	DIN 1629	
Specific minimum characteristics	R_e [MPa]	235
	R_m [MPa]	350
	K_v [J]	No requirements
Material characteristics	R_e [MPa]	347
	R_m [MPa]	490
	K_v [3] [J]	94

[3] Notched-bar impact test as per DIN EN 10045, V-notch, Charpy longitudinal

Table 3.11: Chemical composition of St35

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.116	0.13	0.4	0.032	0.017	0.065	0.02	0.005
	Ni	V	Ti	Nb				
	0.032	0.001	0.001	0001				

Table 3.12: Fracture toughness of St35

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
St35	Base material (100 bar)	41	111.6
St35	Base material (20 bar)	41	111.6
St35	Base material (10 bar)	41	125.3
St35	Base material (5 bar)	41	151.1
St35	Base material (2 bar)	41	135
St35	Base material (1 bar)	41	140.9
St35	Base material (0.2 bar)	41	140.9
St35	Base material (air)	41	173.9

This material was investigated at different hydrogen pressures of 0 bar, 0.2 bar, 1 bar, 2 bar, 5 bar, 10 bar, 20 bar and 100 bar. The crack growth curves are shown below.

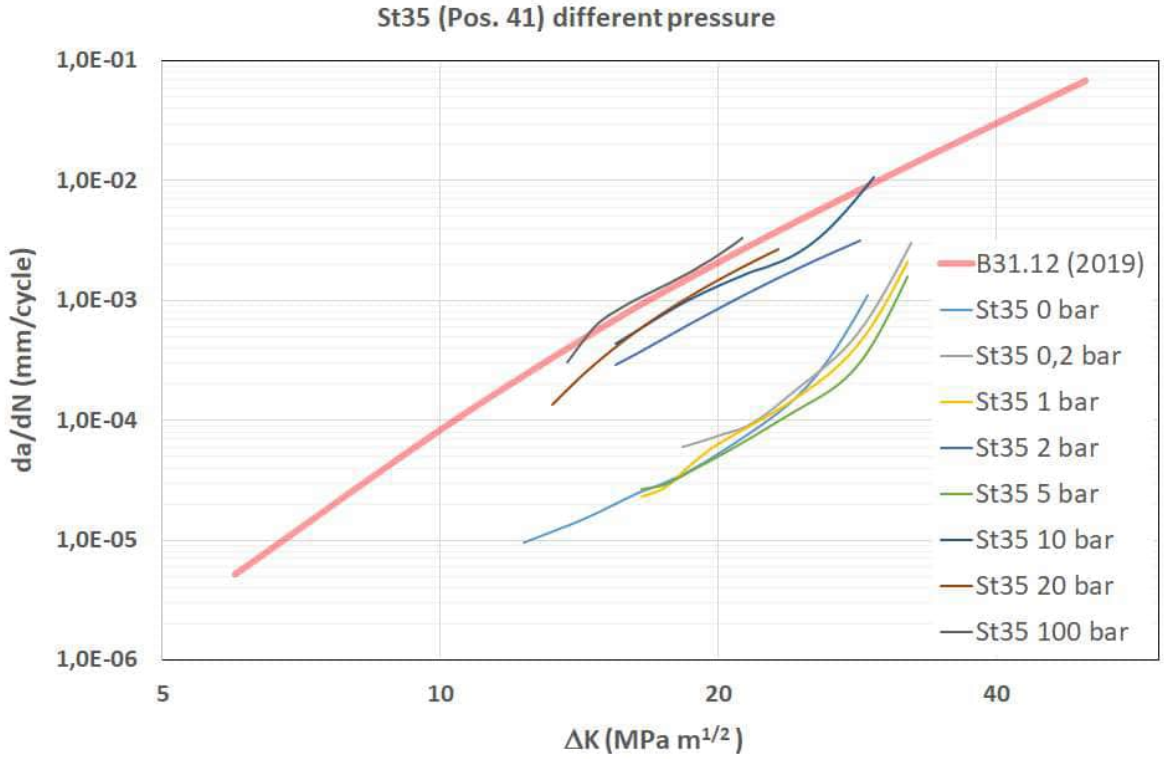


Figure 3.13: Crack growth St35 (item no. 41) at different pressures

3.4 15k (St35)

The samples were taken from a pipe with a diameter of 420 mm and a wall thickness of 8 mm.

The relevant material-specific data is as follows:

Table 3.13: Characteristics of 15k (St35)

Production year	1955	
Production standard	GOST 5520-79	
Specific minimum characteristics	R_e [MPa]	225
	R_m [MPa]	370
	K_v [4] [J]	39
Material characteristics	R_e [MPa]	316
	R_m [MPa]	458
	K_v [J]	Not measured

Table 3.14: Chemical composition of 15k (St35)

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.16	0.13	0.42	0.013	0.043	0.14	0.02	
	Ni	V	Ti	Nb				

Table 3.15: Fracture toughness of 15k (St35)

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
15k (St35)	Base material	23	98.4
15k (St35)	Weld material	23	99.6

The curves describing crack growth in fatigue testing in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material of the longitudinal weld

[4] Transverse notched-bar impact =90°; V-sample as per DIN EN ISO 148-1 at 0 °C

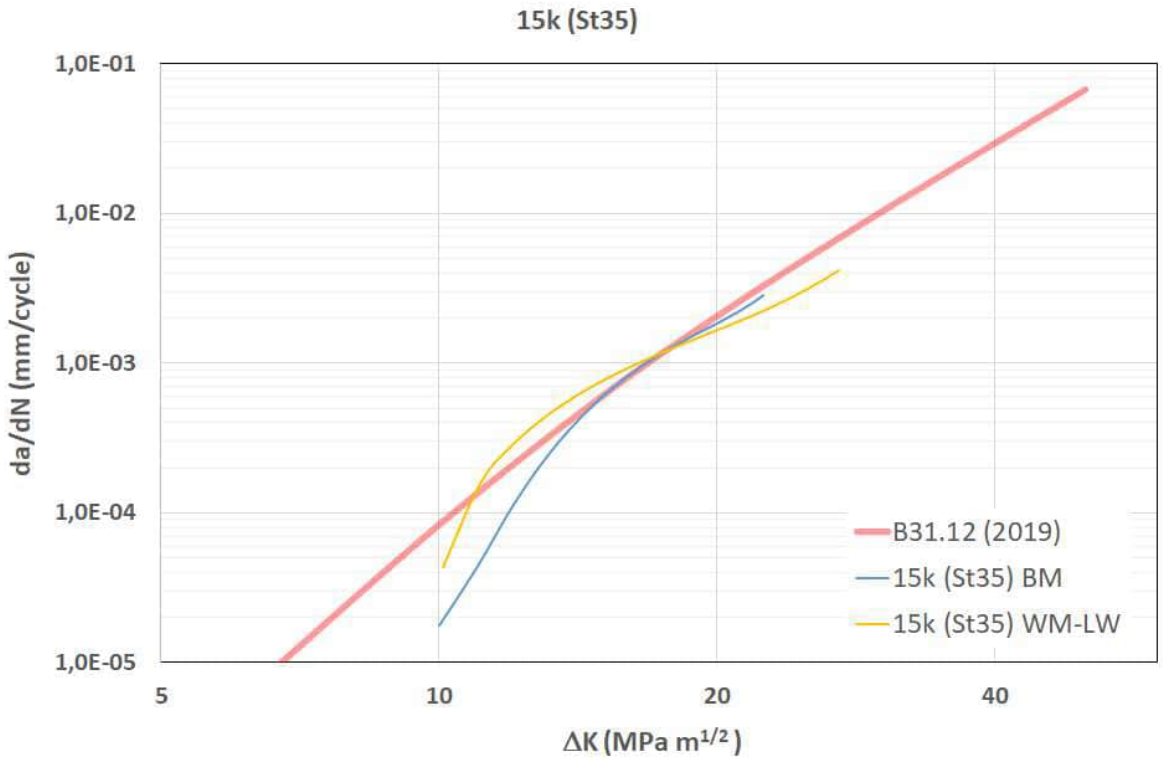


Figure 3.14: Crack growth 15k (St35)

Hardness measurements were performed on four metallographic samples from item no. 23. The results of these hardness measurements are shown in Figures 3.15 to 3.21.

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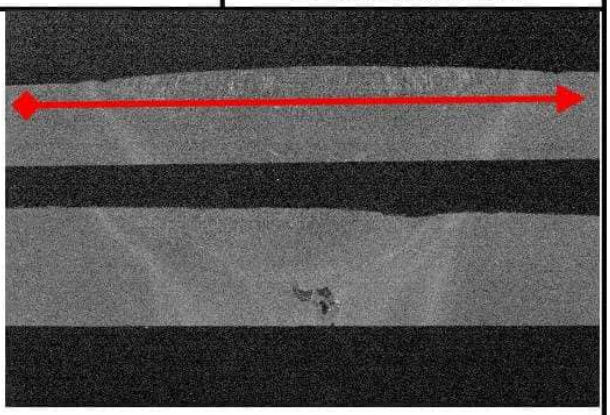
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	23A5S-1 Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	354,3	359,1	0,3567	146	142		BM 1
2	360,5	361,2	0,3608	142			
3	355,3	358,2	0,3568	146			
4	363,7	368,2	0,3659	138			
5	362,8	367,0	0,3649	139			
1	358,5	357,8	0,3581	145	147		HAZ 1
2	358,0	354,7	0,3564	146			
3	353,1	354,3	0,3537	148			
4	354,3	356,6	0,3555	147			
5	354,1	352,0	0,3531	149			
1	343,9	343,5	0,3437	157	155		WM
2	340,8	338,6	0,3397	161			
3	346,4	348,3	0,3474	154			
4	356,0	352,4	0,3542	148			
5	345,6	341,9	0,3437	157			
1	355,3	362,6	0,3590	144	149		HAZ 2
2	344,5	349,3	0,3469	154			
3	347,5	352,3	0,3499	151			
4	351,8	352,0	0,3519	150			
5	353,9	358,3	0,3561	146			
1	354,7	355,3	0,3550	147	142		BM 2
2	354,3	357,4	0,3559	146			
3	363,4	364,9	0,3642	140			
4	363,7	367,6	0,3656	139			
5	365,3	370,5	0,3679	137			

Date: 06.11.22

Tester: Scheck

Figure 3.15: Hardness measurements of 15k (St35) (1)

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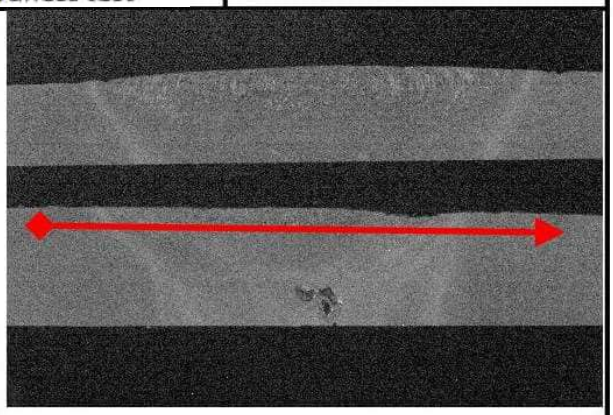
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	23A5S-2 Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	347,7	355,8	0,3517	150	148		BM 1
2	352,3	353,1	0,3527	149			
3	351,6	354,3	0,3530	149			
4	356,4	359,5	0,3579	145			
5	350,6	353,9	0,3522	149			
1	362,2	363,9	0,3630	141	146		HAZ 1
2	353,9	355,4	0,3546	147			
3	355,1	357,2	0,3562	146			
4	354,1	353,3	0,3537	148			
5	353,7	354,9	0,3543	148			
1	352,6	348,9	0,3508	151	151		WM
2	352,0	346,0	0,3490	152			
3	352,4	351,6	0,3520	150			
4	354,7	353,3	0,3540	148			
5	350,2	347,0	0,3486	153			
1	367,2	369,3	0,3682	137	147		HAZ 2
2	352,4	350,4	0,3514	150			
3	353,9	352,4	0,3532	149			
4	353,5	350,8	0,3521	150			
5	352,9	352,4	0,3527	149			
1	360,9	359,7	0,3603	143	147		BM 2
2	353,7	359,7	0,3567	146			
3	349,3	352,7	0,3510	151			
4	351,0	353,1	0,3520	150			
5	351,8	356,6	0,3542	148			

Date: 06.11.22

Tester: Scheck

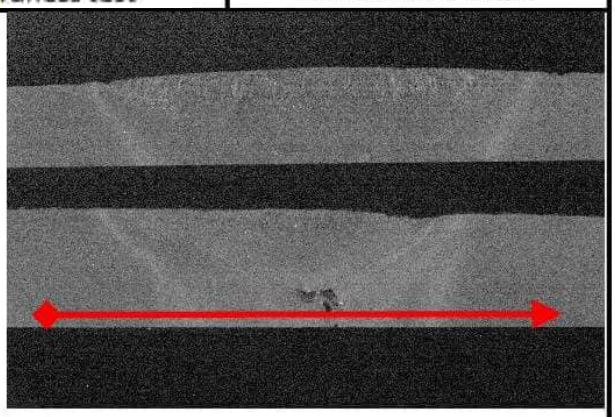
Figure 3.16: Hardness measurements of 15k (St35) (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	23A5S-2 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	359,5	365,1	0,3623	141	144		BM 1
2	362,6	369,9	0,3663	138			
3	357,6	362,0	0,3598	143			
4	361,4	364,7	0,3630	141			
5	340,0	348,1	0,3440	157			
1	374,7	363,2	0,3689	136	146		HAZ 1
2	353,7	351,0	0,3523	149			
3	352,9	351,4	0,3521	150			
4	353,7	352,4	0,3531	149			
5	356,0	353,5	0,3547	147			
1	343,9	340,6	0,3423	158	159		WM
2	342,1	344,3	0,3432	157			
3	336,9	335,8	0,3364	164			
4	337,9	338,7	0,3383	162			
5	348,3	347,9	0,3481	153			
1	356,0	355,5	0,3558	147	148		HAZ 2
2	353,7	352,0	0,3529	149			
3	353,9	353,5	0,3537	148			
4	351,8	351,2	0,3515	150			
5	356,6	357,6	0,3571	145			
1	364,7	365,9	0,3653	139	142		BM 2
2	356,2	359,5	0,3578	145			
3	356,8	367,6	0,3622	141			
4	359,5	361,4	0,3604	143			
5	358,7	363,2	0,3610	142			

Date: 06.11.22

Tester: Scheck

Figure 3.17: Hardness measurements of 15k (St35) (3)

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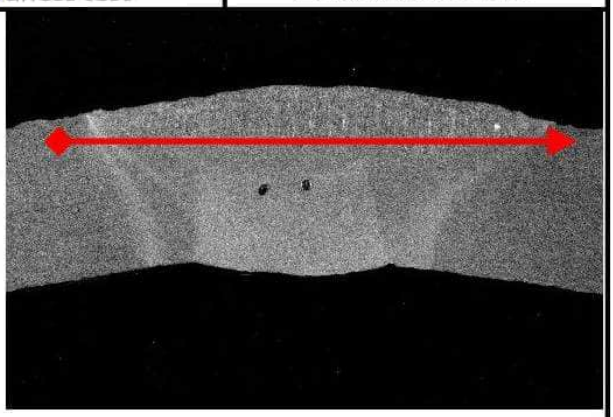
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	23C.1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	355,8	362,8	0,3593	144	145		BM 1
2	355,3	361,4	0,3584	144			
3	348,7	355,6	0,3521	150			
4	352,7	360,7	0,3567	146			
5	357,6	364,7	0,3612	142			
1	347,3	353,5	0,3504	151	156		HAZ 1
2	341,6	343,1	0,3424	158			
3	341,2	345,0	0,3431	158			
4	341,6	345,4	0,3435	157			
5	342,9	346,6	0,3448	156			
1	331,9	328,0	0,3299	170	175		WM
2	325,0	328,8	0,3269	174			
3	325,9	330,0	0,3280	172			
4	327,3	316,7	0,3220	179			
5	322,5	322,3	0,3224	178			
1	347,7	353,3	0,3505	151	153		HAZ 2
2	344,3	350,8	0,3476	154			
3	351,2	344,8	0,3480	153			
4	347,9	350,0	0,3489	152			
5	344,6	347,0	0,3458	155			
1	359,7	361,4	0,3605	143	147		BM 2
2	353,7	357,0	0,3553	147			
3	352,9	359,9	0,3564	146			
4	352,2	354,7	0,3535	148			
5	352,7	354,9	0,3538	148			

Date: 06.11.22

Tester: Scheck

Figure 3.18: Hardness measurements of 15k (St35) (4)

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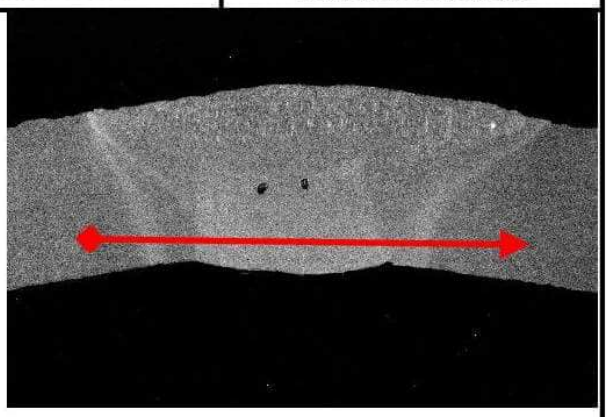
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	23C.1; Root
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	344,8	349,8	0,3473	154	149		BM 1
2	343,3	346,0	0,3447	156			
3	348,9	357,6	0,3533	149			
4	357,4	364,9	0,3612	142			
5	357,6	360,7	0,3592	144			
1	349,9	350,2	0,3501	151	154		HAZ 1
2	352,6	349,8	0,3512	150			
3	343,5	349,1	0,3463	155			
4	341,0	343,1	0,3420	158			
5	344,4	343,8	0,3441	157			
1	332,3	330,6	0,3315	169	166		WM
2	333,3	334,8	0,3341	166			
3	338,9	336,3	0,3376	163			
4	335,2	334,0	0,3346	166			
5	335,2	335,8	0,3355	165			
1	345,6	344,1	0,3449	156	157		HAZ 2
2	353,1	352,0	0,3525	149			
3	341,1	340,8	0,3410	160			
4	340,8	339,5	0,3402	160			
5	342,3	343,7	0,3430	158			
1	362,0	363,9	0,3629	141	140		BM 2
2	363,9	371,5	0,3677	137			
3	365,7	367,8	0,3668	138			
4	363,4	365,7	0,3646	140			
5	355,6	359,5	0,3575	145			

Date: 06.11.22

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Figure 3.19: Hardness measurements of 15k (St35) (5)

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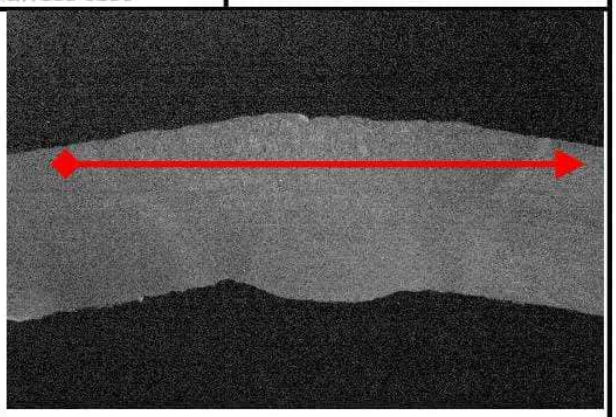
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	23C.2; **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	353,7	358,0	0,3559	146	148		BM 1
2	346,4	349,1	0,3478	153			
3	354,5	359,3	0,3569	146			
4	352,9	359,1	0,3560	146			
5	354,1	356,4	0,3552	147			
1	332,8	§§=;$	0,3328	167	170		HAZ 1
2	331,9	329,6	0,3308	170			
3	330,6	330,8	0,3307	170			
4	333,1	329,6	0,3314	169			
5	327,3	329,0	0,3282	172			
1	316,4	321,5	0,3189	182	182		WM
2	324,2	318,6	0,3214	180			
3	320,3	315,9	0,3181	183			
4	322,1	320,5	0,3213	180			
5	320,7	315,7	0,3182	183			
1	347,0	342,9	0,3450	156	159		HAZ 2
2	344,1	344,1	0,3441	157			
3	339,2	339,6	0,3394	161			
4	343,9	336,7	0,3403	160			
5	340,8	340,4	0,3406	160			
1	354,3	359,9	0,3571	145	145		BM 2
2	357,6	364,3	0,3609	142			
3	357,2	358,9	0,3580	145			
4	355,3	361,6	0,3585	144			
5	353,9	358,0	0,3560	146			

Date: 06.11.22

Tester: Scheck

Figure 3.20: Hardness measurements of 15k (St35) (6)

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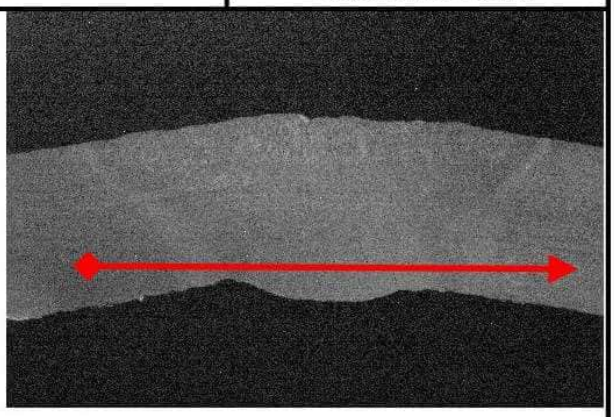
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	23C.2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	342,5	346,2	0,3444	156	152		BM 1
2	343,9	350,4	0,3472	154			
3	350,6	350,8	0,3507	151			
4	354,1	353,7	0,3539	148			
5	349,6	352,7	0,3511	150			
1	330,9	329,8	0,3303	170	156		HAZ 1
2	344,6	343,1	0,3438	157			
3	354,1	351,4	0,3528	149			
4	354,7	351,8	0,3533	149			
5	347,9	346,8	0,3474	154			
1	335,8	333,1	0,3345	166	168		WM
2	335,0	329,2	0,3321	168			
3	335,2	330,6	0,3329	167			
4	329,8	326,5	0,3282	172			
5	333,1	329,6	0,3314	169			
1	347,5	342,3	0,3449	156	155		HAZ 2
2	344,3	340,2	0,3423	158			
3	348,7	344,8	0,3467	154			
4	347,3	343,1	0,3452	156			
5	350,2	346,0	0,3481	153			
1	348,1	353,3	0,3507	151	152		BM 2
2	346,2	349,5	0,3479	153			
3	348,9	351,4	0,3502	151			
4	346,2	352,0	0,3491	152			
5	340,8	351,0	0,3459	155			

Date: 06.11.22

Tester: Scheck

Figure 3.21: Hardness measurements of 15k (St35) (7)

3.5 X42

The samples were taken from a longitudinally electric resistance-welded pipe with a diameter of 406 mm and a wall thickness of 9 mm.

The relevant material-specific data is as follows:

Table 3.16: Characteristics of X42

Production year	1961	
Production standard	DIN 2470 / API Special Regulations (API 5 LX)	
Specific minimum characteristics	R_e [MPa]	289 (29.5 kg/mm^2)
	R_m [MPa]	414 (42.2 kg/mm^2)
	K_v /A [kgm/cm^2]	4
Material characteristics	R_e [MPa]	297 (30.3 kg/mm^2)
	R_m [MPa]	466 (47.6 kg/mm^2)
	K_v [5] /A [kgm/cm^2]	5

Table 3.17: Chemical composition of X42

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.17	0.24	0.65	0.013	0.042			
	Ni	V	Ti	Nb				

Table 3.18: Fracture toughness of X42

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
X42	Base material	3	88.6
X42	Girth weld	3	118.6
X42	Heat-affected zone of girth weld	3	115.7
X42	Electric resistance weld 1/2	3	104.1/105.2

The curves describing crack growth in fatigue testing in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material (GW)
- electric resistance-welded longitudinal weld (ERW)
- girth weld (GW)
- heat-affected zone of the girth weld

[5] Transverse notched-bar impact =0°; DVM as per DIN 50116

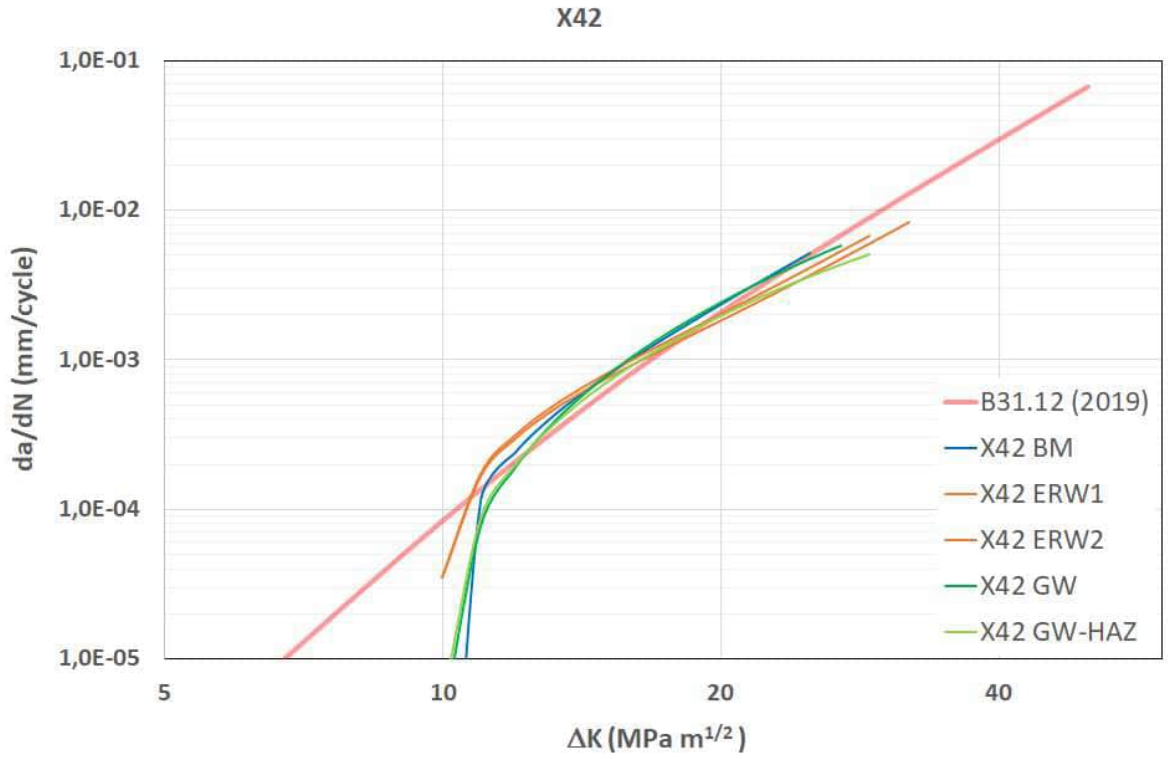


Figure 3.22: Crack growth X42

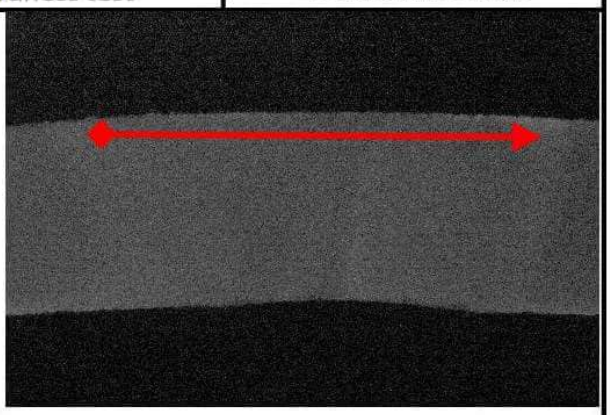
Hardness measurements were performed on two metallographic samples from item no. 3. The results of these hardness measurements are shown in Figures 3.23 to 3.26.

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	3LN-1 Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	312,4	319,0	0,3157	186			
2	312,6	318,0	0,3153	187			
3	310,3	316,9	0,3136	189			
4	308,8	316,1	0,3125	190			
5	309,3	314,7	0,3120	191			
6	308,6	313,2	0,3109	192			
7	309,7	313,2	0,3114	191			
8	310,9	314,2	0,3126	190			
9	310,1	313,0	0,3116	191			
10	308,9	312,8	0,3108	192			
11	309,7	313,4	0,3116	191			
12	310,1	312,0	0,3110	192			
13	311,3	313,0	0,3122	190			
14	311,5	311,1	0,3113	191			
15	305,7	303,3	0,3045	200			
16	305,5	305,7	0,3056	199			
17	310,5	312,6	0,3116	191			
18	311,3	312,6	0,3120	191			
19	310,1	312,6	0,3113	191			
20	311,1	314,0	0,3126	190			
21	311,6	314,0	0,3128	190			
22	309,9	312,0	0,3109	192			
23	306,8	309,9	0,3083	195			

Date: 06.11.22

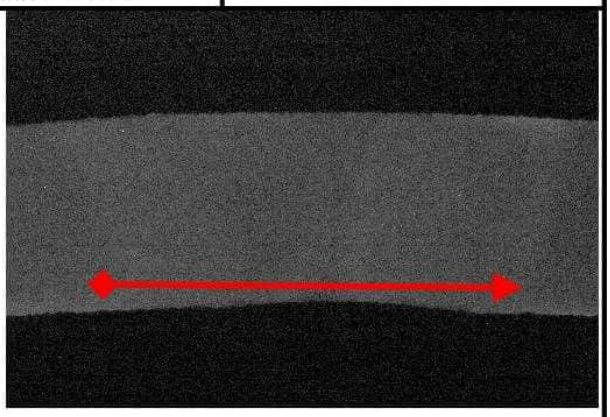
Tester: Scheck

Figure 3.23: Hardness measurements of X42 (1)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	3 LN-1 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	311,5	318,2	0,3149	187			
2	313,0	320,1	0,3165	185			
3	317,4	321,5	0,3194	182			
4	316,7	323,4	0,3201	181			
5	315,7	318,8	0,3173	184			
6	319,0	323,2	0,3211	180			
7	319,9	324,4	0,3221	179			
8	320,5	325,2	0,3229	178			
9	321,9	323,0	0,3224	178			
10	318,6	324,2	0,3214	180			
11	318,0	322,3	0,3202	181			
12	318,4	321,7	0,3201	181			
13	317,0	314,0	0,3155	186			
14	311,6	311,1	0,3113	191			
15	320,5	322,3	0,3214	180			
16	319,0	320,9	0,3200	181			
17	317,6	321,7	0,3196	181			
18	317,8	321,3	0,3195	182			
19	318,8	321,7	0,3203	181			
20	320,3	322,5	0,3214	180			
21	319,6	322,1	0,3209	180			
22	313,2	317,8	0,3155	186			

Date: 06.11.22

Tester: Scheck

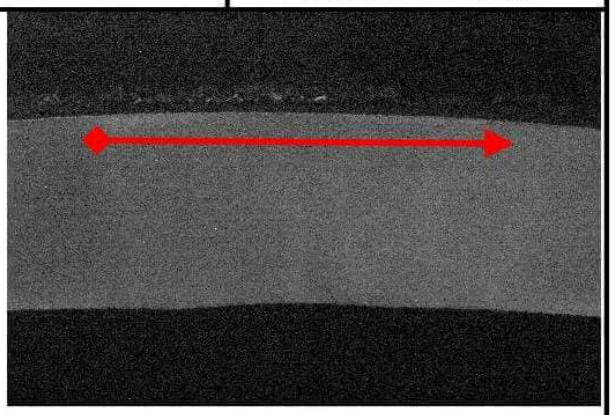
Figure 3.24: Hardness measurements of X42 (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	3 LN-2 Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	308,4	314,3	0,3113	191			
2	309,3	315,7	0,3125	190			
3	305,3	313,2	0,3093	194			
4	306,4	311,3	0,3089	194			
5	310,9	315,7	0,3133	189			
6	307,8	310,3	0,3091	194			
7	312,8	315,1	0,3139	188			
8	310,3	311,3	0,3108	192			
9	310,5	312,2	0,3113	191			
10	310,7	311,5	0,3111	192			
11	306,8	311,3	0,3091	194			
12	307,6	310,3	0,3090	194			
13	301,8	301,0	0,3014	204			
14	307,4	304,5	0,3059	198			
15	309,9	313,8	0,3119	191			
16	310,1	313,0	0,3116	191			
17	308,6	313,6	0,3111	192			
18	310,7	312,8	0,3118	191			
19	312,6	315,1	0,3138	188			
20	312,6	315,3	0,3139	188			
21	312,4	315,7	0,3140	188			
22	310,7	315,3	0,3130	189			
23	311,6	316,5	0,3140	188			
24	313,6	318,4	0,3160	186			

Date: 06.11.22

Tester: Scheck

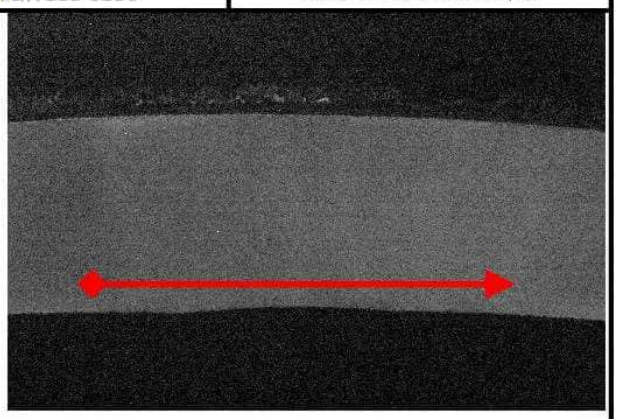
Figure 3.25: Hardness measurements of X42 (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und
Elektronenmikroskopie

Order number	9039784000
Sample description	3 LN-2 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	306,4	314,0	0,3102	193			
2	306,8	314,2	0,3105	192			
3	307,8	313,4	0,3106	192			
4	308,4	312,8	0,3106	192			
5	310,5	312,6	0,3116	191			
6	314,7	318,8	0,3167	185			
7	318,2	320,3	0,3192	182			
8	319,9	322,3	0,3211	180			
9	318,2	322,4	0,3203	181			
10	318,0	320,9	0,3194	182			
11	319,2	320,3	0,3198	181			
12	318,6	320,7	0,3196	181			
13	321,9	323,0	0,3224	178			
14	315,9	313,8	0,3149	187			
15	319,8	318,2	0,3190	182			
16	317,4	322,8	0,3201	181			
17	320,3	323,8	0,3220	179			
18	319,4	323,0	0,3212	180			
19	320,3	323,2	0,3217	179			
20	320,1	321,1	0,3206	180			
21	317,8	323,2	0,3205	181			
22	316,1	323,0	0,3195	182			
23	316,3	323,4	0,3199	181			
24	314,7	323,2	0,3189	182			

Date: 06.11.22

Tester: Scheck

Figure 3.26: Hardness measurements of X42 (4)

3.6 RR St43.7

The samples were taken from a seamless pipe with a diameter of 406.4 mm and a wall thickness of 14.2 mm.

The relevant material-specific data is as follows:

Table 3.19: Characteristics of RR St43.7

Production year	1972	
Production standard	DIN 17172	
Specific minimum characteristics	R_e [MPa]	294
	R_m [MPa]	422
	K_v /A [kgm/cm^2]	4
Material characteristics	R_e [MPa]	318
	R_m [MPa]	487
	K_v /A [kgm/cm^2]	Not measured

Table 3.20: Chemical composition of RR St43.7

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.17	0.26	0.93	0.0025	0.0017			
	Ni	V	Ti	Nb				

Table 3.21: Fracture toughness of RR St43.7

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
RR St43.7	Base material	22	101.9

For fatigue testing in a purely hydrogen atmosphere at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5, the samples were taken from the base material. The relevant crack growth curve is shown below.

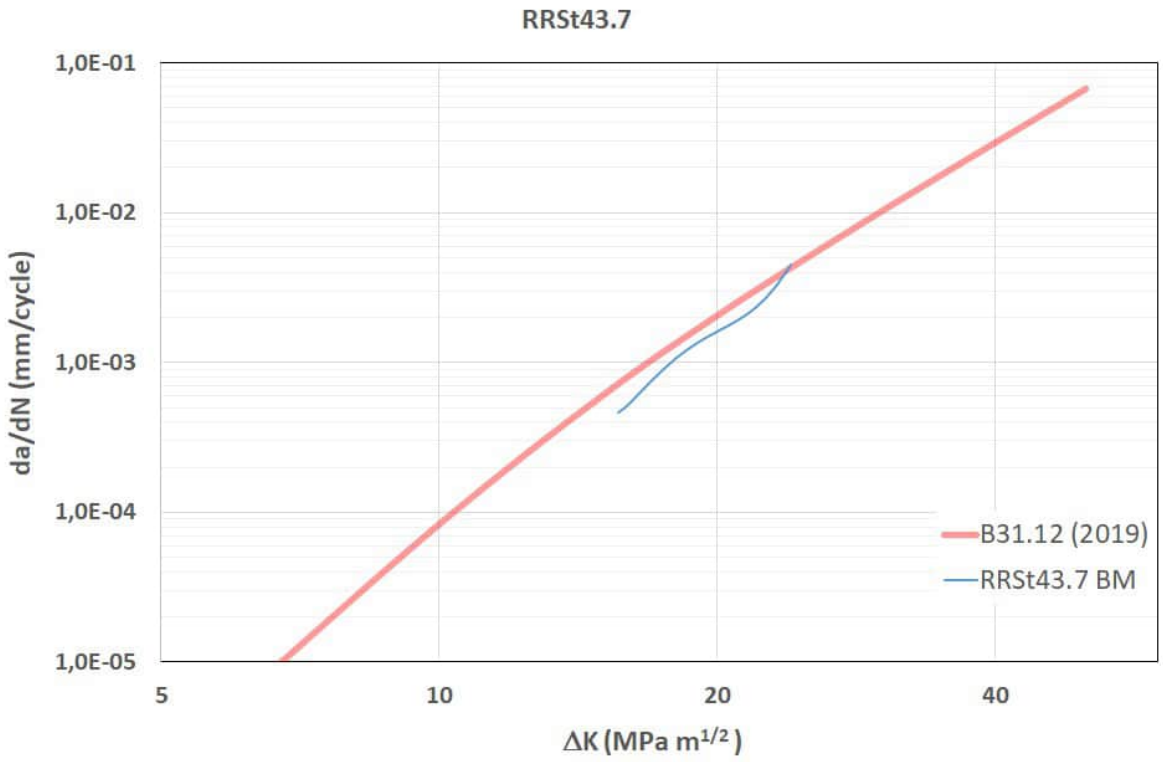


Figure 3.27: Crack growth RRSt43.7

3.7 P355 NH/NL2

The samples were taken from a plate with a thickness of 15 mm.

The relevant material-specific data is as follows:

Table 3.22: Characteristics of P355 NH/NL2

Production year	2019	
Production standard	DIN EN 10028-3 (10/17)	
Specific minimum characteristics	R_e [MPa]	355
	R_m [MPa]	490
	K_v [6] [J]	27
Material characteristics	R_e [MPa]	389
	R_m [MPa]	541
	K_v [6] [J]	108

Table 3.23: Chemical composition of P355 NH/NL2

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.18	0.34	1.19	0.009	0.001	0.2	0.03	0.003
	Ni	V	Ti	Nb				
	0.25	0.009	0.005	0.02				

Table 3.24: Fracture toughness of P355 NH/NL2

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
P355NH	Base material	13	101.9

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the base material.

[6] V-sample as per DIN EN ISO 148-1 at -50 °C

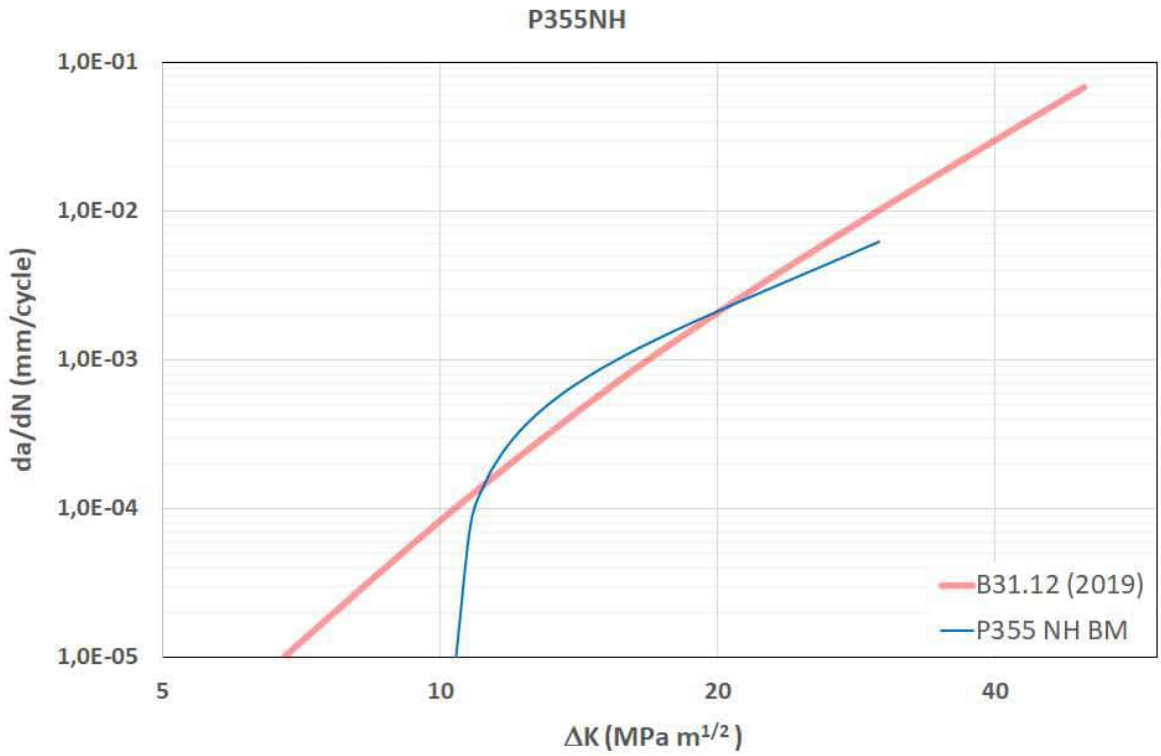


Figure 3.28: Crack growth P355 NH

3.8 L360NE

The samples were taken from an HFI longitudinally welded pipe with a diameter of 400 mm and wall thickness of 10 mm.

The relevant material-specific data is as follows:

Table 3.25: Characteristics of L360NE

Production year	2018	
Production standard	ISO 3183 (11/12) M	
Specific minimum characteristics	R_e [MPa]	360
	R_m [MPa]	460
	K_v [J]	40
Material characteristics	R_e [MPa]	445
	R_m [MPa]	570
	K_v [7] [J]	190

Table 3.26: Chemical composition of L360NE

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.15	0.21	1.42	0.012	0.001	0.03	0.04	0.004
	Ni	V	Ti	Nb				
	0.04	0.002	0.003	0.03				

Table 3.27: Fracture toughness of L360NE

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
L360 NE	Base material	7	151.1

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5, 0.1 and 0.7.

Samples were taken from the base material.

[7] Testing in line with Charpy, longitudinal; V-notch at -20 °C

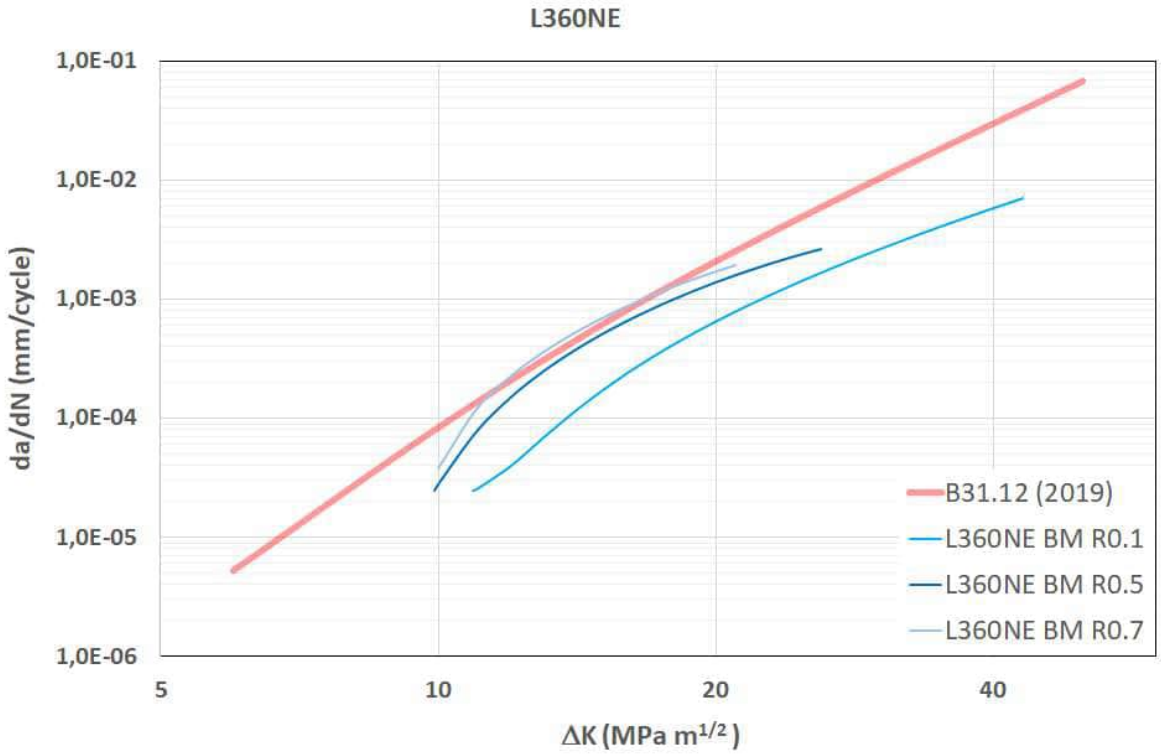


Figure 3.29: Crack growth L360 NE

3.9 L360NB (Batch 2)

The samples were taken from a pipe with a diameter of 406.4 mm and a wall thickness of 12.5 mm.

The relevant material-specific data is as follows:

Table 3.28: Characteristics of L360NB

Production year	2010	
Production standard	EN 10208-2	
Specific minimum characteristics	R_e [MPa]	360
	R_m [MPa]	460
	K_v [J]	40
Material characteristics	R_e [MPa]	449
	R_m [MPa]	592
	K_v [J]	145

Table 3.29: Chemical composition of L360NB

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.15	0.18	1.39	0.014	0.002	0.05	0.05	0
	Ni	V	Ti	Nb				
	0.04	0	0	0.02				

Table 3.30: Fracture toughness of L360NB

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
L360NB	Base material	Batch 2	150 (100 bar) / 148 (10 bar)
L360NB	Weld material	Batch 2	140 (100 bar) / 164 (10 bar)

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar and 10 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material

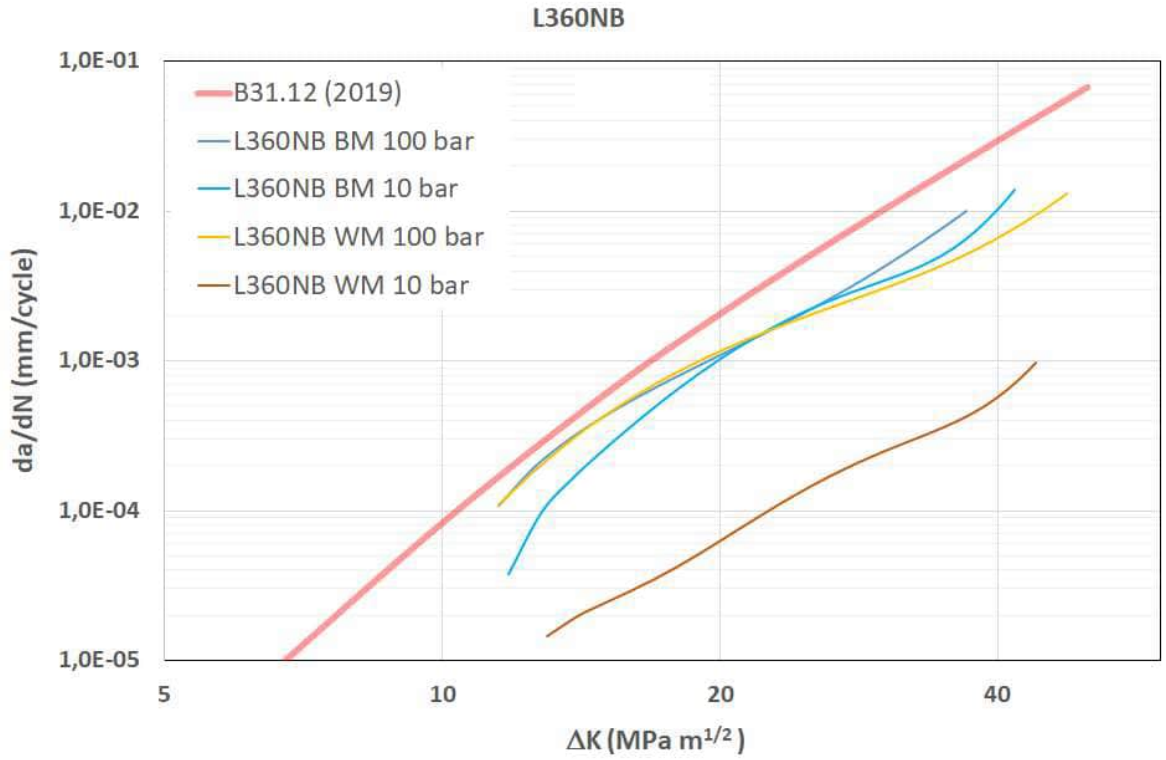


Figure 3.30: Crack growth L360NB

3.10 X46 / StE320.7

The samples were taken from a pipe with a diameter of 406.4 mm and a wall thickness of 8.8 mm.

The relevant material-specific data is as follows:

Table 3.31: Characteristics of X46 / StE320.7

Production year	1964	
Production standard	DIN 17172	
Specific minimum characteristics	R_e [MPa]	320
	R_m [MPa]	460
	K_v [J]	47
Material characteristics	R_e [MPa]	Ø 413
	R_m [MPa]	Ø 528
	K_v [J]	Ø 107

Table 3.32: Chemical composition of X46 / StE320.7

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.23	0.23	0.94	0.015	0.037	0.18	0.04	0.01
	Ni	V	Ti	Nb				
	0.05	0	0	0.01				

Table 3.33: Fracture toughness of X46 / StE320.7

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
X46 / StE320.7	Base material		85 (100 bar) / 91 (10 bar)
X46 / StE320.7	Weld material of girth weld		115 (100 bar) / 135 (10 bar)

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar and 10 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material of the girth weld

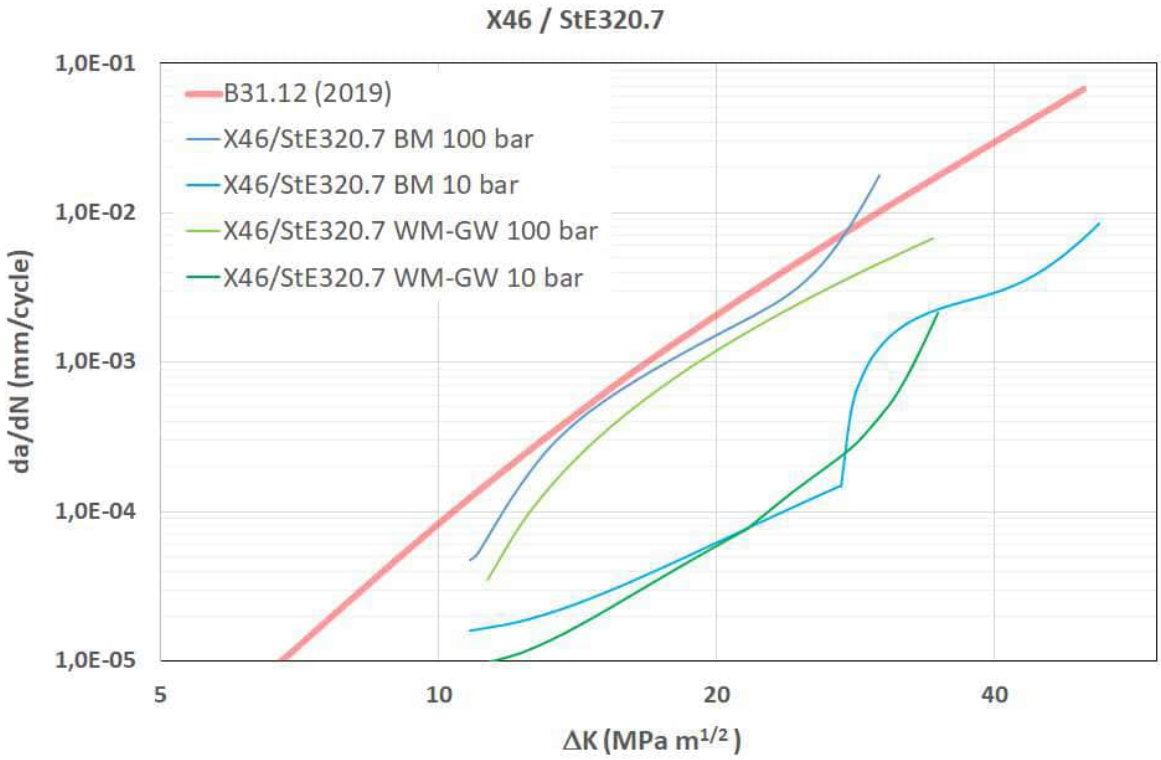


Figure 3.31: Crack growth X46 / StE320.7

3.11 StE360.7

The samples were taken from an HF longitudinally welded pipe with a diameter of 273 mm and a wall thickness of 8 mm.

The relevant material-specific data is as follows:

Table 3.34: Characteristics of StE360.7

Production year	1996	
Production standard	DIN 17172	
Specific minimum characteristics	R_e [MPa]	360
	R_m [MPa]	510
	K_v [J]	47
Material characteristics	R_e [MPa]	451
	R_m [MPa]	554
	K_v [J]	281

Table 3.35: Chemical composition of StE360.7

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.105	0.151	1.1	0.02	0.005			
	Ni	V	Ti	Nb				
		0.001						

Table 3.36: Fracture toughness of StE360.7

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
StE360.7	Base material	18	135.9
StE360.7	Longitudinal weld	18	81.8

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the base material and the longitudinal weld (LW).

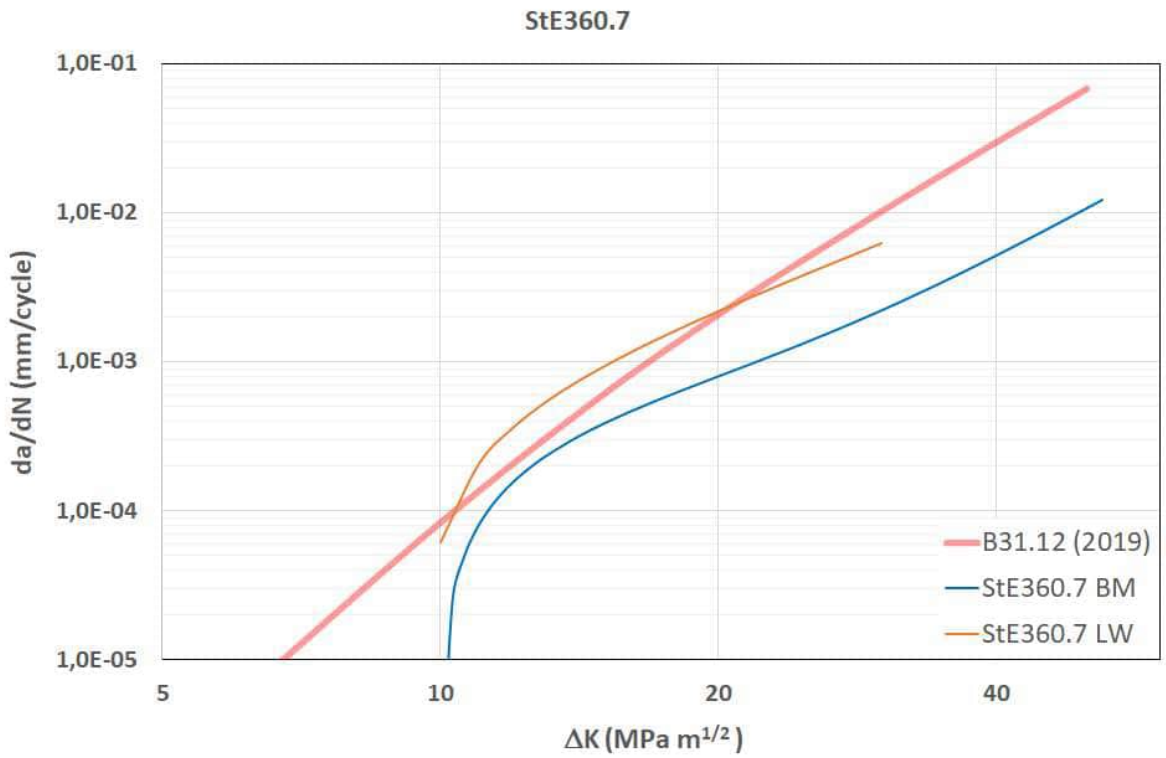


Figure 3.32: Crack growth StE360.7

Hardness measurements were performed on two metallographic samples from item no. 18. The results of these hardness measurements are shown in Figures 3.33 to 3.36.

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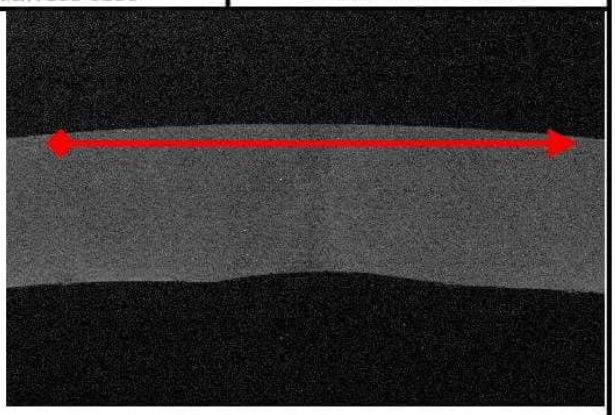

Order number	9039784000
Sample description	18.1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV 10 — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	292,5	300,8	0,2966	211			
2	293,9	301,6	0,2977	209			
3	294,9	301,6	0,2983	208			
4	292,0	298,9	0,2955	212			
5	291,2	297,0	0,2941	214			
6	288,5	295,6	0,2920	217			
7	289,1	293,9	0,2915	218			
8	286,9	292,7	0,2898	221			
9	285,6	291,0	0,2883	223			
10	284,2	290,6	0,2874	225			
11	281,9	275,2	0,2785	239			
12	273,2	267,5	0,2704	254			
13	278,3	287,7	0,2830	232			
14	280,2	287,9	0,2840	230			
15	287,3	290,2	0,2887	222			
16	284,6	287,3	0,2859	227			
17	283,3	289,5	0,2864	226			
18	287,9	288,7	0,2883	223			
19	289,6	293,1	0,2913	219			
20	287,7	294,3	0,2910	219			
21	287,9	290,2	0,2890	222			
22	287,9	283,6	0,2857	227			

Date: 06.11.22

Tester: Scheck

Figure 3.33: Hardness measurements of StE360.7 (1)

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Hardness test

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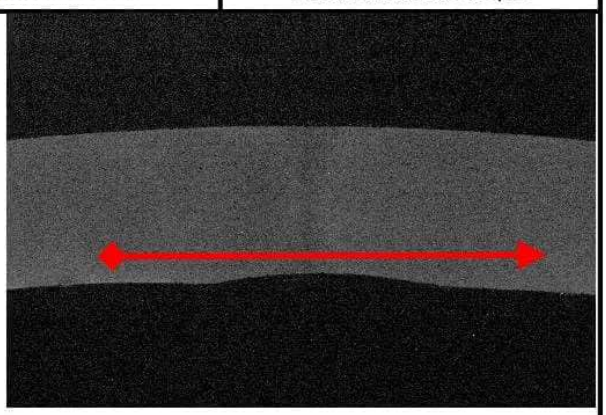
Order number	9039784000
Sample description	18.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV **10**	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	294,1	296,0	0,2951	213			
2	292,7	304,3	0,2985	208			
3	294,3	305,3	0,2998	206			
4	294,7	303,9	0,2993	207			
5	294,9	305,1	0,3000	206			
6	293,3	304,7	0,2990	207			
7	295,8	303,0	0,2994	207			
8	294,3	302,2	0,2983	208			
9	293,3	300,3	0,2968	210			
10	292,5	296,8	0,2946	214			
11	285,8	291,6	0,2887	222			
12	289,4	293,7	0,2915	218			
13	291,8	298,9	0,2954	213			
14	283,9	291,6	0,2878	224			
15	288,3	294,5	0,2914	218			
16	294,9	298,7	0,2968	210			
17	293,9	299,7	0,2968	210			
18	293,9	301,8	0,2979	209			
19	291,2	296,8	0,2940	215			
20	291,4	298,5	0,2949	213			

Date: 06.11.22

Tester: Scheck

Figure 3.34: Hardness measurements of StE360.7 (2)

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Hardness test

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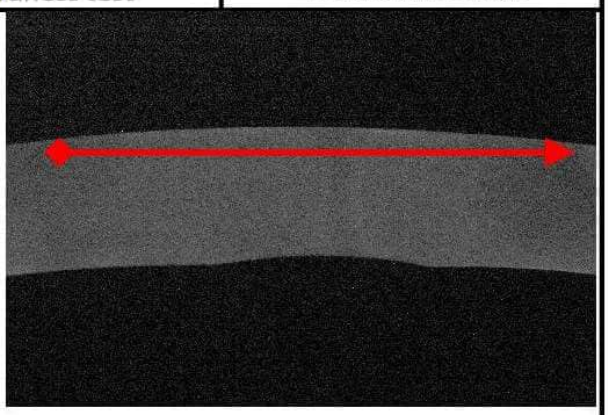

Order number	9039784000
Sample description	18.2; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV 10 — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	290,4	292,7	0,2915	218			
2	288,7	292,9	0,2908	219			
3	284,8	290,8	0,2878	224			
4	285,4	288,9	0,2872	225			
5	287,1	288,7	0,2879	224			
6	286,0	287,7	0,2869	225			
7	281,0	286,9	0,2839	230			
8	282,3	288,5	0,2854	228			
9	284,2	287,7	0,2859	227			
10	285,8	285,6	0,2857	227			
11	284,0	283,1	0,2835	231			
12	284,4	288,9	0,2867	226			
13	286,6	292,7	0,2897	221			
14	287,5	293,3	0,2904	220			
15	288,9	291,8	0,2904	220			
16	288,7	295,8	0,2922	217			
17	291,0	297,2	0,2941	214			
18	292,7	297,0	0,2948	213			
19	296,8	302,8	0,2998	206			

Date: 06.11.22

Tester: Scheck

Figure 3.35: Hardness measurements of StE360.7 (3)

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Hardness test

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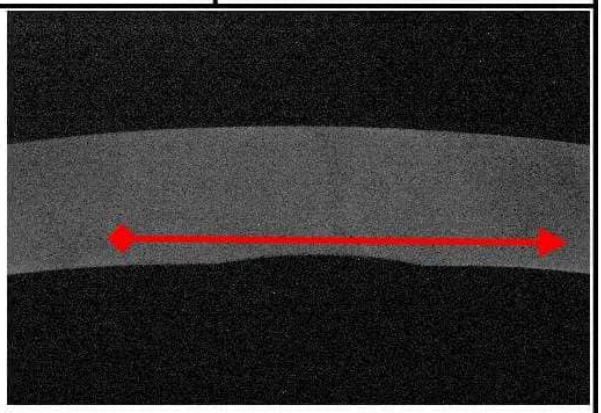

Order number	9039784000
Sample description	18.2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV **10** DIN EN ISO 6507-1:2018-07
- ☐ HBW DIN EN ISO 6506-1:2015-02
- ☐ HRC DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	294,3	300,3	0,2973	210			
2	293,5	301,0	0,2972	210			
3	296,6	301,0	0,2988	208			
4	294,7	300,6	0,2976	209			
5	292,0	299,7	0,2959	212			
6	292,9	298,7	0,2958	212			
7	293,1	298,5	0,2958	212			
8	290,2	296,2	0,2932	216			
9	288,9	296,6	0,2928	216			
10	288,9	296,2	0,2926	217			
11	278,8	276,3	0,2775	241			
12	292,3	299,5	0,2959	212			
13	290,0	298,7	0,2943	214			
14	291,4	301,4	0,2964	211			
15	296,4	304,7	0,3006	205			
16	294,9	303,0	0,2990	207			
17	292,9	302,2	0,2975	209			
18	293,9	303,0	0,2985	208			
19	292,7	304,3	0,2985	208			

Date: 06.11.22

Tester: Scheck

Figure 3.36: Hardness measurements of StE360.7 (4)

3.12 StE480.7 TM

The samples were taken from a pipe with a diameter of 813 mm and a wall thickness of 13.4 mm.

The relevant material-specific data is as follows:

Table 3.37: Characteristics of StE480.7 TM

Production year	1997	
Production standard	DIN 17172	
Specific minimum characteristics	R_e [MPa]	480
	R_m [MPa]	600
	K_v [J]	48
Material characteristics	R_e [MPa]	508
	R_m [MPa]	616
	K_v [J]	253

Table 3.38: Chemical composition of StE480.7 TM

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.09	0.39	1.59	0.013	0.001	0.03	0.03	0.01
	Ni	V	Ti	Nb				
	0.04	0.06	0.00	0.04				

Table 3.39: Fracture toughness of StE480.7 TM

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
StE480.7 TM	Base material		138 (100 bar) / 132 (10 bar)
StE480.7 TM	Weld material of longitudinal weld		146 (100 bar) / 190 (10 bar)
StE480.7 TM	Weld material of the girth weld		139 (100 bar) / 145 (10 bar)

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar and 10 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material of the longitudinal weld
- weld material of the girth weld (WM-GW)

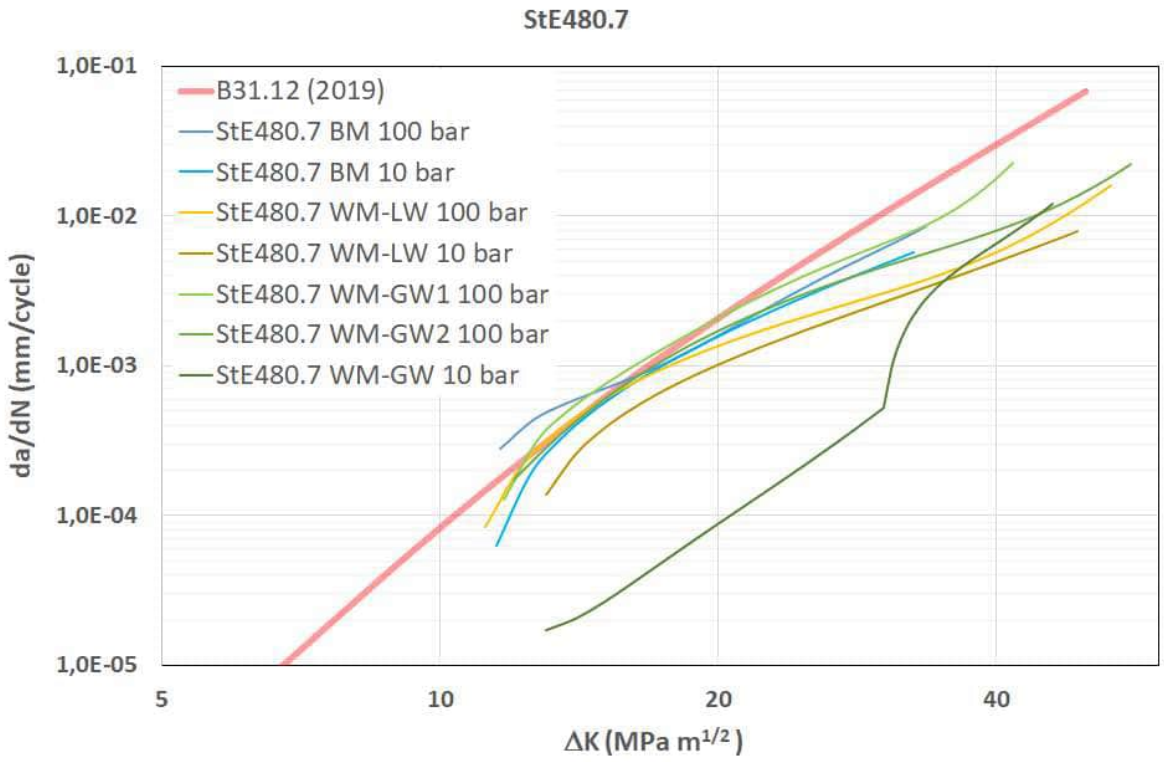

Figure 3.37: Crack growth StE480.7 TM

3.13 L360 NB

The samples were taken from an HFI longitudinally welded pipe with a diameter of 400 mm and a wall thickness of 8 mm.

The relevant material-specific data is as follows:

Table 3.40: Characteristics of L360 NB

Production year	2013	
Production standard	DIN EN 10208-2	
Specific minimum characteristics	R_e [MPa]	360
	R_m [MPa]	460
	K_v [8] [J]	40
Material characteristics	R_e [MPa]	423
	R_m [MPa]	583
	K_v [8] [J]	156

Table 3.41: Chemical composition of L360 NB

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.15	0.19	1.39	0.09	0.001	0.02	0.04	0.01
	Ni	V	Ti	Nb				
	0.03	0.004	0.03	0.027				

Table 3.42: Fracture toughness of L360 NB

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
L360 NB	Base material	20	128
L360 NB	Weld material of longitudinal weld	20	132.4

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the base material and the longitudinal weld.

[8] V-sample as per DIN EN ISO 148-1 at 0 °C

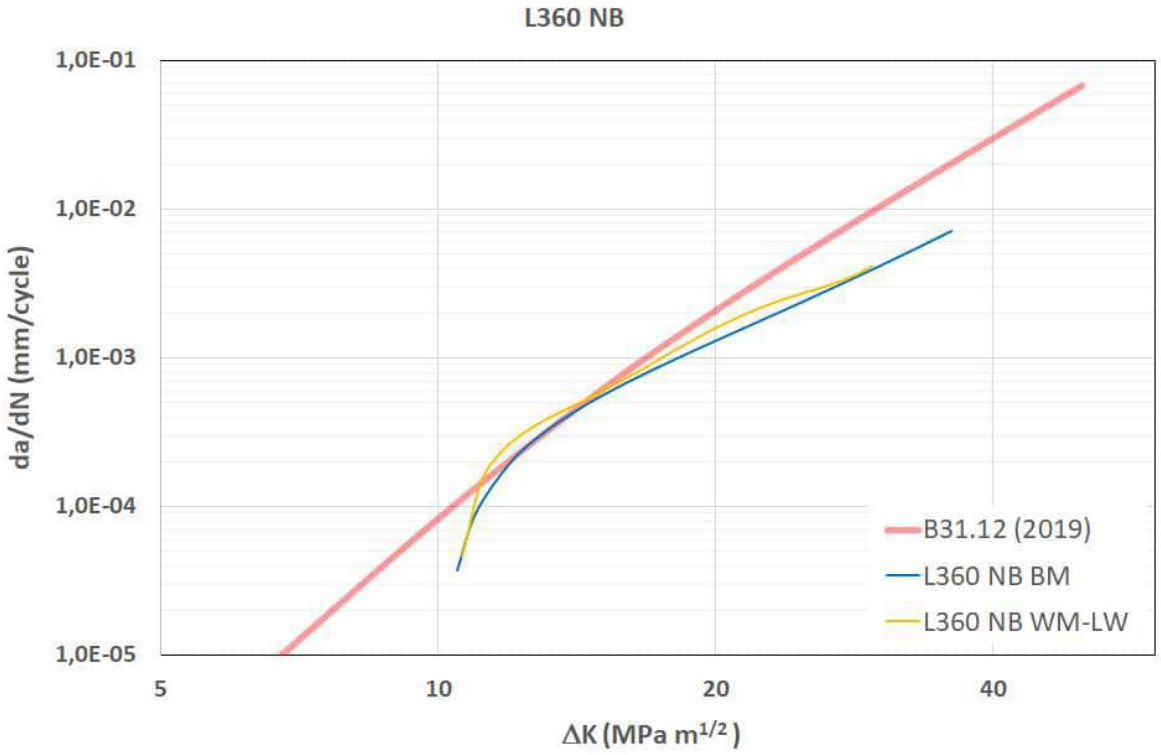

Figure 3.38: Crack growth L360 NB

Hardness measurements were performed on two metallographic samples from item no. 20. The results of these hardness measurements are shown in Figures 3.39 bis 3.42.

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Test report
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Hardness test

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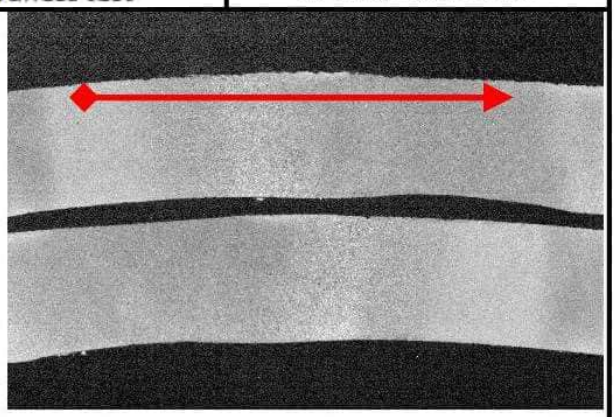
Order number	9039784000
Sample description	20HFLN-1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	293	301	0,2970	210			
2	294,5	301,4	0,2980	209			
3	270,7	280,6	0,2756	244			
4	262,2	263,6	0,2629	268			
5	262,8	265,1	0,2639	266			
6	259,9	261,9	0,2609	272			
7	258,2	259,0	0,2586	277			
8	253,8	256,1	0,2550	285			
9	255,7	256,1	0,2559	283			
10	255,7	255,7	0,2557	284			
11	264,5	259,4	0,2620	270			
12	270,0	273,4	0,2717	251			
13	275,0	275,6	0,2753	245			
14	285,4	289,6	0,2875	224			
15	292,2	293,1	0,2927	216			
16	293,5	296,0	0,2947	213			
17	291,4	291,8	0,2916	218			
18	290,6	292,0	0,2913	219			
19	295,4	291,2	0,2933	216			
20	294,1	295,6	0,2948	213			
21	289,8	293,3	0,2915	218			
22	291,2	291,8	0,2915	218			
23	287,1	290,6	0,2888	222			
24	287,9	287,3	0,2876	224			
25	291,0	291,4	0,2912	219			
26	292,7	295,8	0,2942	214			
27	295,4	299,1	0,2972	210			

Date: 06.11.22

Tester: Scheck

Figure 3.39: Hardness measurements of L360 NB (1)

MPA STUTTGART

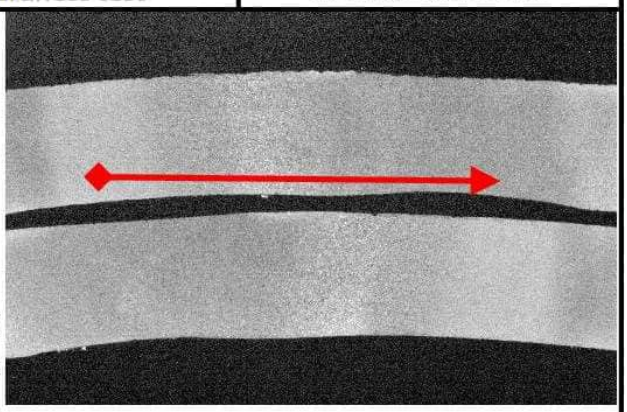
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	20HFLN-1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV **10**	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	290,0	300,1	0,2951	213			
2	283,9	294,5	0,2892	222			
3	283,7	286,4	0,2851	228			
4	282,7	286,4	0,2846	229			
5	281,7	285,6	0,2836	230			
6	276,1	279,4	0,2777	240			
7	266,1	267,3	0,2667	261			
8	255,5	259,0	0,2573	280			
9	251,2	259,4	0,2553	285			
10	258,6	262,4	0,2605	273			
11	272,1	272,5	0,2723	250			
12	282,9	283,7	0,2833	231			
13	291,6	294,3	0,2930	216			
14	297,9	301,8	0,2998	206			
15	298,9	299,7	0,2993	207			
16	299,3	302,0	0,3007	205			
17	298,5	301,8	0,3001	206			
18	298,7	303,9	0,3013	204			
19	302,4	299,9	0,3012	204			
20	299,9	303,2	0,3016	204			
21	302,2	302,2	0,3022	203			
22	302,6	305,7	0,3042	200			
23	303,2	306,2	0,3047	200			

Date: 06.11.22

Tester: Scheck

Figure 3.40: Hardness measurements of L360 NB (2)

MPA STUTTGART

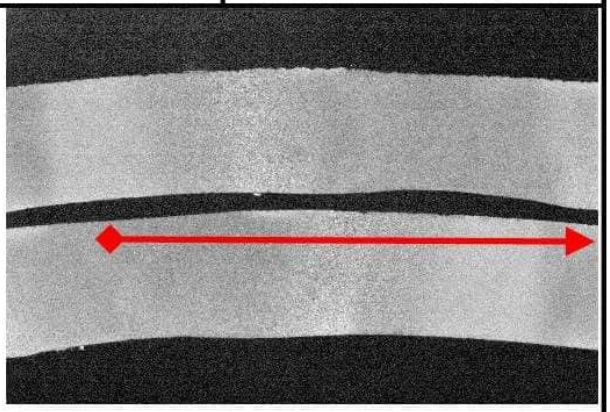
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	20HFLN-2, Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑ HV	10	DIN EN ISO 6507-1:2018-07
☐ HBW		DIN EN ISO 6506-1:2015-02
☐ HRC		DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	294,3	295,2	0,2947	213			
2	295,2	295,4	0,2953	213			
3	288,9	291,6	0,2903	220			
4	284,4	287,7	0,2860	227			
5	288,7	288,3	0,2885	223			
6	289,4	285,8	0,2876	224			
7	290,2	294,1	0,2921	217			
8	288,9	293,7	0,2913	219			
9	289,1	293,3	0,2912	219			
10	288,7	288,9	0,2888	222			
11	292,0	294,3	0,2932	216			
12	289,8	294,3	0,2920	217			
13	287,7	288,5	0,2881	223			
14	279,2	280,6	0,2799	237			
15	264,9	272,7	0,2688	257			
16	260,9	265,3	0,2631	268			
17	253,0	254,3	0,2537	288			
18	255,5	259,5	0,2575	280			
19	254,9	258,6	0,2568	281			
20	255,7	256,1	0,2559	283			
21	261,7	261,9	0,2618	270			
22	268,6	266,9	0,2678	259			
23	268,4	268,2	0,2683	258			
24	268,2	278,3	0,2733	248			

Date: 06.11.22

Tester: Scheck

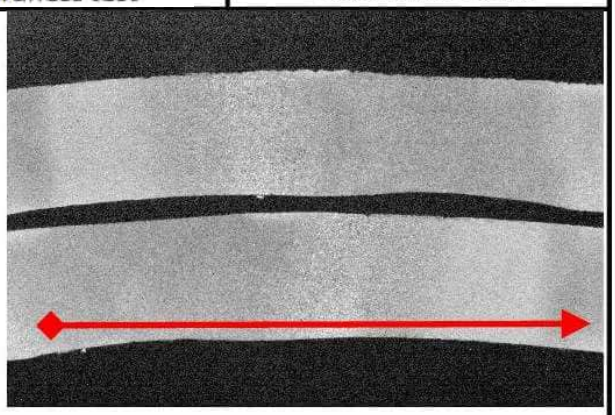
Figure 3.41: Hardness measurements of L360 NB (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	20HFLN-2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	**235 HV**	Reference:	**237 HV 10**

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	296,8	299,1	0,2980	209			
2	302,8	303,9	0,3034	202			
3	304,7	306,8	0,3057	198			
4	304,9	306,6	0,3057	198			
5	304,5	305,3	0,3049	199			
6	301,2	303,2	0,3022	203			
7	302,8	303,0	0,3029	202			
8	300,3	302,4	0,3014	204			
9	299,7	302,6	0,3012	204			
10	302,4	304,3	0,3033	202			
11	300,1	300,1	0,3001	206			
12	291,4	294,3	0,2929	216			
13	283,3	283,1	0,2832	231			
14	275,0	272,3	0,2737	248			
15	261,3	264,6	0,2630	268			
16	254,7	257,2	0,2559	283			
17	254,7	256,8	0,2557	284			
18	265,9	267,8	0,2668	260			
19	273,8	279,2	0,2765	243			
20	280,2	284,8	0,2825	232			
21	285,4	289,3	0,2874	225			
22	283,3	287,7	0,2855	228			
23	279,6	292,9	0,2862	226			

Date: 06.11.22

Tester: Scheck

Figure 3.42: Hardness measurements of L360 NB (4)

3.14 14HGS

The samples were taken from a pipe with a diameter of 529 mm and a wall thickness of 9 mm.

The relevant material-specific data is as follows:

Table 3.43: Characteristics 14HGS

Production year	1964	
Production standard	GOST 5058 -65	
Specific minimum characteristics	R_e [MPa]	343
	R_m [MPa]	491
	K_v /A [kgm/cm^2]	4
Material characteristics	R_e [MPa]	392 (40 kp/mm^2)
	R_m [MPa]	510 (52 kp/mm^2)
	K_v /A [kgm/cm^2][9]	5

Table 3.44: Chemical composition of 14HGS

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.149	0.48	1.05	0.032	0.025	0.13	0.70	0.005
	Ni	V	Ti	Nb				
	0.07	0.002	0.009	<0.001				

Table 3.45: Fracture toughness of 14HGS

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
14HGS	Base material	21	105.2
14HGS	Weld material of longitudinal weld	21	105.2
14HGS	Weld material of the girth weld	21	100.8

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- longitudinal weld
- girth weld

[9] Notched-bar impact test performed at -40 °C

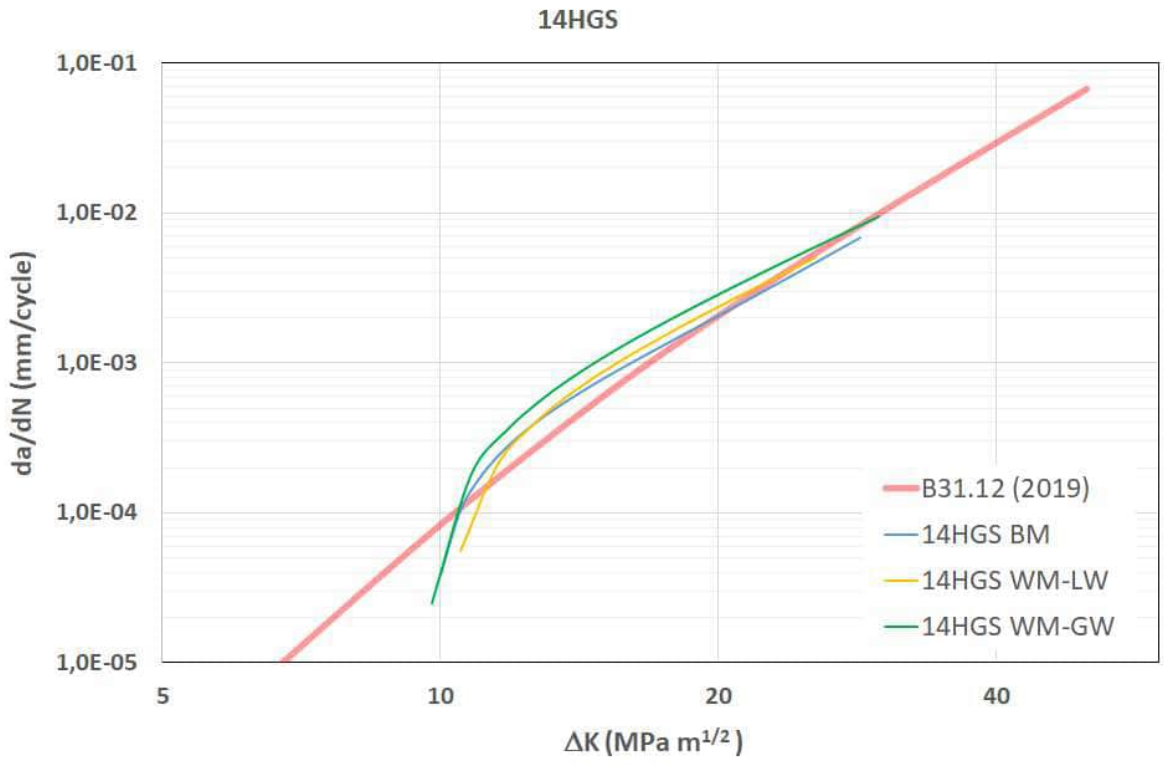


Figure 3.43: Crack growth 14HGS

Hardness measurements were performed on four metallographic samples from item no. 21. The results of these hardness measurements are shown in Figures 3.44 to 3.53.

MPA STUTTGART

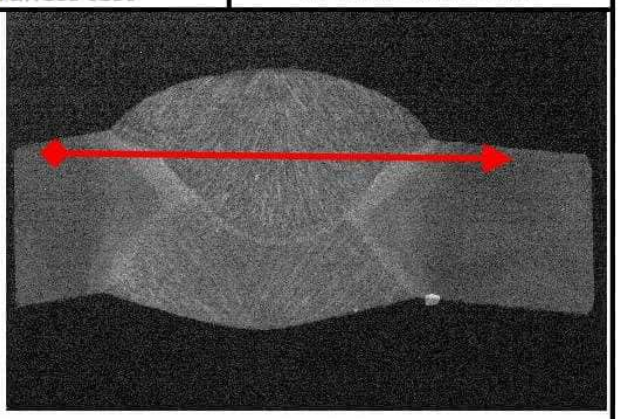
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21LN-1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	330,6	327,1	0,3289	171	168		BM 1
2	329,2	331,3	0,3302	170			
3	331,9	334,2	0,3330	167			
4	335,2	335,6	0,3354	165			
5	333,1	333,6	0,3333	167			
1	308,4	308,0	0,3082	195	208		HAZ 1
2	302,2	301,4	0,3018	204			
3	294,3	299,3	0,2968	210			
4	293,5	292,0	0,2928	216			
5	294,5	294,9	0,2947	213			
1	329,4	329,8	0,3296	171	171		WM
2	332,7	331,9	0,3323	168			
3	329,6	326,7	0,3282	172			
4	322,2	322,4	0,3223	179			
5	333,3	333,6	0,3334	167			
1	313,8	313,0	0,3134	189	204		HAZ 2
2	304,3	303,0	0,3037	201			
3	297,6	299,5	0,2986	208			
4	297,0	300,5	0,2988	208			
5	294,5	292,0	0,2933	216			
1	328,6	327,8	0,3282	172	173		BM 2
2	324,4	324,0	0,3242	176			
3	326,3	325,2	0,3258	175			
4	327,7	328,6	0,3282	172			
5	331,1	328,4	0,3297	171			

Date: 06.11.22

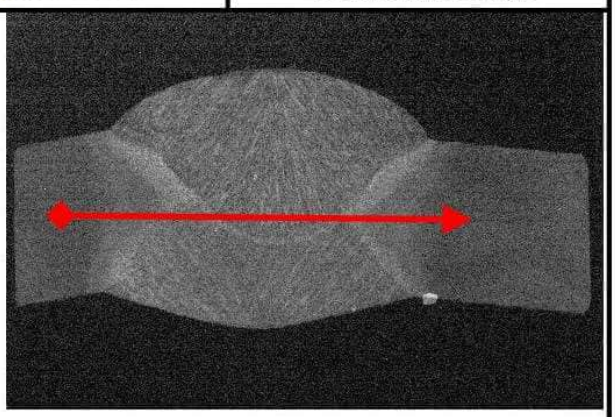
Tester: Scheck

Figure 3.44: Hardness measurements of 14HGS (1)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	21LN-1; Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	326,1	330,0	0,3281	172	167		BM 1
2	332,3	331,5	0,3319	168			
3	333,8	330,6	0,3322	168			
4	334,6	340,0	0,3373	163			
5	335,6	337,1	0,3364	164			
1	301,0	296,4	0,2987	208	199		HAZ 1
2	300,8	300,8	0,3008	205			
3	302,0	301,6	0,3018	204			
4	308,2	305,7	0,3070	197			
5	321,7	319,0	0,3204	181			
1	340,2	332,1	0,3362	164	168		WM
2	331,5	330,0	0,3307	170			
3	333,8	330,6	0,3322	168			
4	332,5	333,3	0,3329	167			
5	330,6	326,3	0,3285	172			
1	303,5	298,7	0,3011	205	202		HAZ 2
2	304,7	297,2	0,3010	205			
3	303,5	304,9	0,3042	200			
4	298,7	299,5	0,2991	207			
5	309,7	308,2	0,3090	194			
1	332,7	338,8	0,3357	165	169		BM 2
2	327,1	334,4	0,3308	169			
3	327,1	331,5	0,3293	171			
4	328,8	328,4	0,3286	172			
5	331,1	328,2	0,3296	171			

Date: 06.11.22

Tester: Scheck

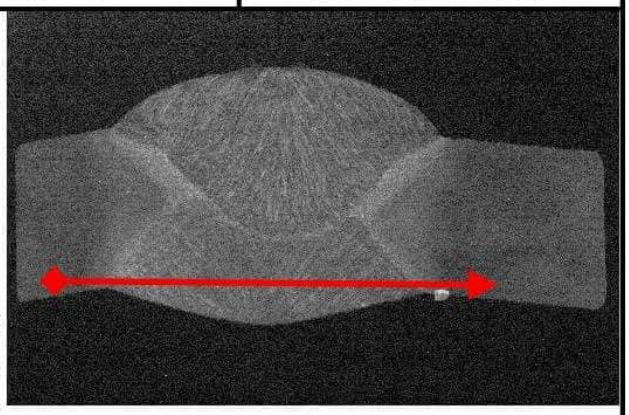
Figure 3.45: Hardness measurements of 14HGS (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21LN-1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	329,2	331,3	0,3302	170	170		BM 1
2	326,1	326,3	0,3262	174			
3	331,9	331,1	0,3315	169			
4	327,1	333,4	0,3302	170			
5	331,1	333,5	0,3323	168			
1	315,7	314,9	0,3153	187	193		HAZ 1
2	295,4	296,2	0,2958	212			
3	299,9	300,1	0,3000	206			
4	320,7	312,2	0,3164	185			
5	327,1	326,5	0,3268	174			
1	336,7	336,5	0,3366	164	167		WM
2	333,1	329,4	0,3313	169			
3	333,2	327,7	0,3305	170			
4	334,2	329,8	0,3320	168			
5	337,1	333,1	0,3351	165			
1	309,1	307,0	0,3080	195	190		HAZ 2
2	312,6	310,1	0,3113	191			
3	315,5	310,1	0,3128	190			
4	310,3	308,6	0,3095	194			
5	323,2	322,1	0,3227	178			
1	331,3	327,3	0,3293	171	175		BM 2
2	321,9	325,2	0,3236	177			
3	324,0	325,0	0,3245	176			
4	324,3	328,6	0,3264	174			
5	325,9	324,0	0,3250	176			

Date: 06.11.22

Tester: Scheck

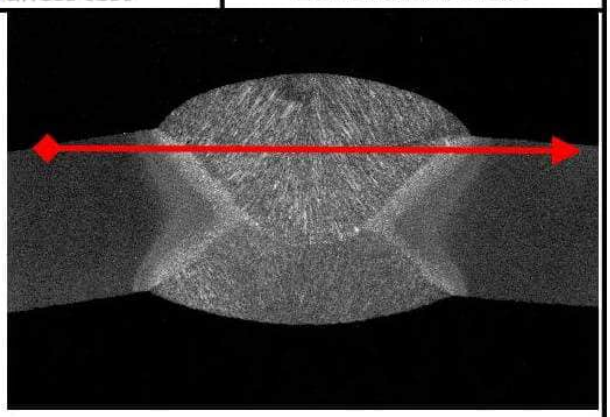
Figure 3.46: Hardness measurements of 14HGS (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21LN-2, Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	310,1	308,9	0,3095	194	192		BM 1
2	312,8	310,5	0,3117	191			
3	310,7	308,4	0,3096	193			
4	310,9	314,3	0,3126	190			
5	312,0	312,6	0,3123	190			
1	287,3	284,6	0,2859	227	231		HAZ 1
2	279,6	281,9	0,2807	235			
3	279,8	280,4	0,2801	236			
4	284,2	286,6	0,2854	228			
5	286,6	283,9	0,2853	228			
1	322,3	314,2	0,3183	183	186		WM
2	318,4	313,8	0,3161	186			
3	321,7	312,8	0,3173	184			
4	312,8	301,2	0,3070	197			
5	317,8	319,9	0,3188	182			
1	284,4	285,8	0,2851	228	225		HAZ 2
2	287,1	282,1	0,2846	229			
3	282,7	285,4	0,2841	230			
4	288,9	288,7	0,2888	222			
5	292,9	290,2	0,2915	218			
1	312,6	314,0	0,3133	189	186		BM 2
2	312,0	314,3	0,3131	189			
3	318,4	315,1	0,3167	185			
4	315,7	315,3	0,3155	186			
5	317,6	319,2	0,3184	183			

Date: 06.11.22

Tester: Scheck

Figure 3.47: Hardness measurements of 14HGS (4)

MPA STUTTGART

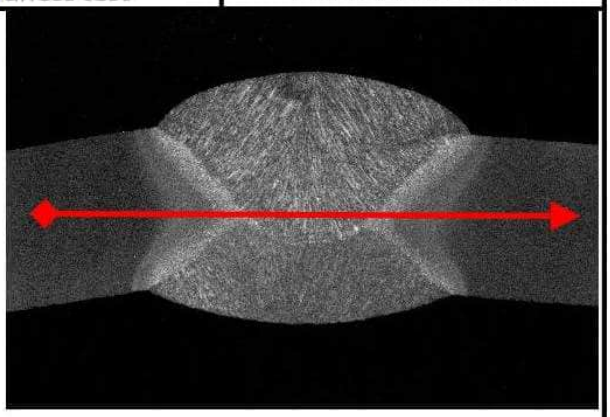
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21LN-2, Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	323,9	329,6	0,3267	174	176		BM 1
2	325,9	327,7	0,3268	174			
3	322,1	327,7	0,3249	176			
4	318,4	322,8	0,3206	180			
5	322,4	326,1	0,3242	176			
1	290,0	293,3	0,2916	218	212		HAZ 1
2	292,2	296,0	0,2941	214			
3	295,4	299,1	0,2972	210			
4	296,2	299,1	0,2976	209			
5	299,5	299,3	0,2994	207			
1	330,2	330,9	0,3305	170	171		WM
2	330,2	326,9	0,3286	172			
3	330,3	327,9	0,3291	171			
4	336,0	323,4	0,3297	171			
5	328,2	333,4	0,3308	170			
1	292,7	296,0	0,2943	214	210		HAZ 2
2	297,2	299,1	0,2982	209			
3	296,8	297,8	0,2973	210			
4	297,9	297,8	0,2979	209			
5	298,1	301,2	0,2996	207			
1	329,4	331,7	0,3305	170	172		BM 2
2	326,3	330,6	0,3285	172			
3	326,7	329,4	0,3281	172			
4	326,5	327,3	0,3269	174			
5	326,3	331,1	0,3287	172			

Date: 06.11.22

Tester: Scheck

Figure 3.48: Hardness measurements of 14HGS (5)

MPA STUTTGART

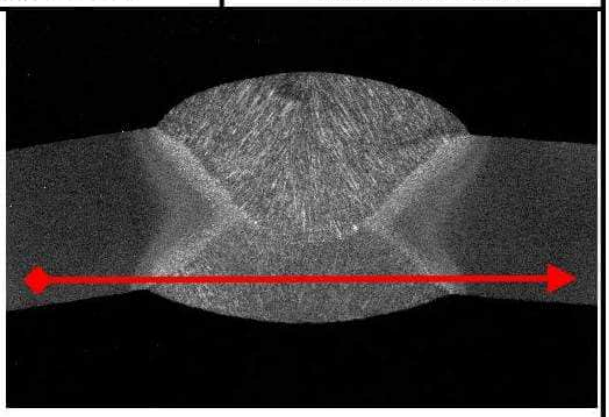
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21LN-2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV **10** — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	312,0	316,7	0,3144	188	190		BM 1
2	310,1	312,8	0,3115	191			
3	309,7	313,2	0,3114	191			
4	310,1	313,0	0,3116	191			
5	315,1	312,0	0,3135	189			
1	306,8	302,0	0,3044	200	203		HAZ 1
2	294,5	292,5	0,2935	215			
3	295,6	300,1	0,2979	209			
4	307,4	308,8	0,3081	195			
5	307,4	305,7	0,3066	197			
1	334,6	326,1	0,3303	170	169		WM
2	333,8	332,1	0,3329	167			
3	331,7	326,9	0,3293	171			
4	332,7	330,7	0,3317	169			
5	336,0	330,0	0,3330	167			
1	303,7	301,2	0,3024	203	199		HAZ 2
2	305,1	304,5	0,3048	200			
3	307,6	309,1	0,3083	195			
4	304,3	301,2	0,3027	202			
5	310,5	308,6	0,3096	193			
1	321,3	320,9	0,3211	180	184		BM 2
2	316,1	315,9	0,3160	186			
3	312,8	316,9	0,3149	187			
4	317,4	317,6	0,3175	184			
5	316,5	317,6	0,3171	184			

Date: 06.11.22

Tester: Scheck

Figure 3.49: Hardness measurements of 14HGS (6)

MPA STUTTGART

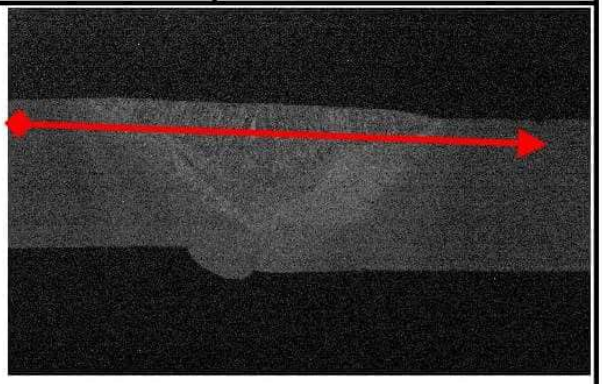
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21 UN (2); **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV **10** — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	323,2	324,7	0,3240	177	172		BM 1
2	326,8	326,8	0,3268	174			
3	331,4	328,6	0,3300	170			
4	333,9	327,8	0,3309	169			
5	331,9	332,4	0,3321	168			
1	365,0	327,0	0,3460	155	198		HAZ 1
2	297,9	303,3	0,3006	205			
3	292,1	298,2	0,2951	213			
4	295,4	293,1	0,2942	214			
5	301,0	304,1	0,3025	203			
1	315,6	320,1	0,3178	184	185		WM
2	323,2	315,3	0,3192	182			
3	311,0	306,9	0,3089	194			
4	327,8	316,1	0,3219	179			
5	315,8	313,3	0,3145	187			
1	304,1	301,0	0,3025	203	210		HAZ 2
2	300,2	298,2	0,2992	207			
3	294,4	294,9	0,2946	214			
4	294,9	299,5	0,2972	210			
5	294,1	294,9	0,2945	214			
1	330,8	330,8	0,3308	169	176		BM 2
2	327,8	328,0	0,3279	172			
3	322,4	322,2	0,3223	179			
4	322,4	323,2	0,3228	178			
5	320,4	321,2	0,3208	180			

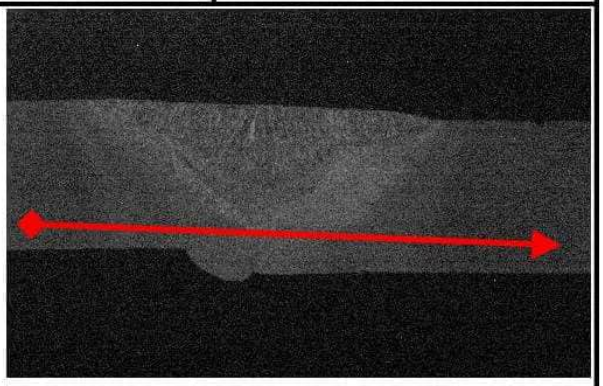
Date: 06.11.22

Tester: Scheck

Figure 3.50: Hardness measurements of 14HGS (7)

MPA STUTTGART	**Test report** MPAS-PPB 52310-08/1 Hardness test	**Referat** Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21 UN (1); **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	326,0	325,5	0,3257	175	169		BM 1
2	331,1	330,8	0,3310	169			
3	329,1	332,9	0,3310	169			
4	332,6	336,0	0,3343	166			
5	333,9	334,4	0,3342	166			
1	317,3	319,4	0,3183	183	189		HAZ 1
2	313,0	313,2	0,3131	189			
3	307,4	312,0	0,3097	193			
4	311,7	311,2	0,3115	191			
5	313,2	313,2	0,3132	189			
1	330,6	333,9	0,3323	168	169		WM
2	329,8	331,9	0,3308	169			
3	333,1	332,6	0,3329	167			
4	329,6	329,8	0,3297	171			
5	332,9	330,8	0,3319	168			
1	307,9	308,7	0,3083	195	201		HAZ 2
2	308,1	308,7	0,3084	195			
3	306,1	307,6	0,3069	197			
4	305,1	301,8	0,3034	201			
5	290,5	294,9	0,2927	216			
1	339,3	336,2	0,3377	163	169		BM 2
2	333,4	335,2	0,3343	166			
3	330,3	331,9	0,3311	169			
4	329,3	327,5	0,3284	172			
5	325,2	326,3	0,3257	175			

Date: 06.11.22

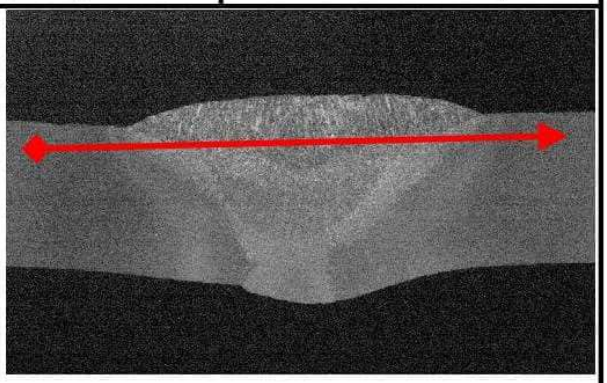
Tester: Scheck

Figure 3.51: Hardness measurements of 14HGS (8)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	21 UN (1), Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	311,3	314,9	0,3131	189	185		BM 1
2	311,8	320,2	0,3160	186			
3	311,8	314,9	0,3133	189			
4	316,3	319,2	0,3178	184			
5	321,5	322,1	0,3218	179			
1	329,4	329,8	0,3296	171	198		HAZ 1
2	306,0	308,9	0,3074	196			
3	294,7	302,0	0,2984	208			
4	298,9	294,5	0,2967	211			
5	302,4	299,5	0,3010	205			
1	319,2	320,9	0,3201	181	179		WM
2	324,0	324,4	0,3242	176			
3	316,3	320,3	0,3183	183			
4	321,5	311,3	0,3164	185			
5	330,2	327,9	0,3291	171			
1	298,5	295,8	0,2971	210	205		HAZ 2
2	303,9	303,5	0,3037	201			
3	297,6	296,0	0,2968	210			
4	305,1	307,2	0,3062	198			
5	298,7	298,3	0,2985	208			
1	332,3	332,1	0,3322	168	174		BM 2
2	330,2	331,7	0,3310	169			
3	324,0	324,6	0,3243	176			
4	319,5	326,9	0,3232	178			
5	325,1	321,1	0,3231	178			

Date: 06.11.22

Tester: Scheck

Figure 3.52: Hardness measurements of 14HGS (9)

MPA STUTTGART

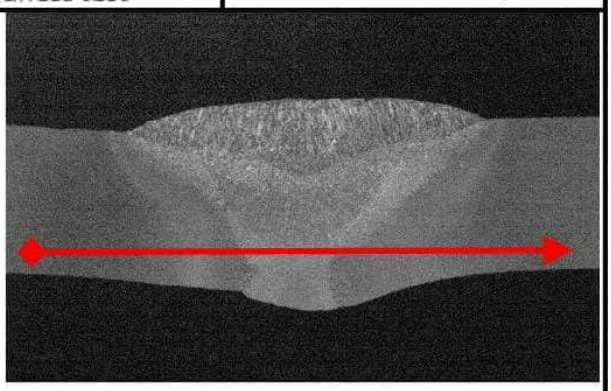
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	21 UN (1); **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV **10** — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	318,2	318,2	0,3182	183	168		BM 1
2	327,3	326,9	0,3271	173			
3	335,8	332,9	0,3344	166			
4	342,3	343,3	0,3428	158			
5	339,6	341,2	0,3404	160			
1	335,2	337,7	0,3365	164	172		HAZ 1
2	331,5	328,6	0,3300	170			
3	325,9	326,9	0,3264	174			
4	321,3	319,0	0,3202	181			
5	326,7	327,5	0,3271	173			
1	339,6	335,4	0,3375	163	162		WM
2	337,5	336,7	0,3371	163			
3	332,5	335,2	0,3339	166			
4	337,9	339,2	0,3385	162			
5	343,9	345,0	0,3444	156			
1	328,8	324,8	0,3268	174	168		HAZ 2
2	328,6	328,8	0,3287	172			
3	332,1	328,8	0,3304	170			
4	337,1	334,8	0,3359	164			
5	340,8	336,9	0,3389	161			
1	337,7	330,9	0,3343	166	174		BM 2
2	327,1	331,3	0,3292	171			
3	328,2	324,6	0,3264	174			
4	323,4	321,7	0,3226	178			
5	319,4	325,3	0,3224	178			

Date: 06.11.22

Tester: Scheck

Figure 3.53: Hardness measurements of 14HGS (10)

3.15 WSTE 420

The samples were taken from a normalised plate with a thickness of 15 mm.

Its base material has the following mechanical properties:

Table 3.46: Characteristics of WSTE 420

Production year	2010	
Production standard	DIN 17102	
Specific minimum characteristics	R_e [MPa]	420
	R_m [MPa]	530
	K_v [J]	21
Material characteristics	R_e [MPa]	416
	R_m [MPa]	542
	K_v [10] [J]	179

Table 3.47: Chemical composition of WSTE 420

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.18	0.2	1.57	0.007	0.001	0.02	0.05	0.01
	Ni	V	Ti	Nb				
	0.58	0.18	0.001	0.002				

Table 3.48: Fracture toughness of WSTE 420

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
WSTE 420	Base material	10	99.6

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[10] Sample produced as per ISO-V 450; test performed at -20 °C

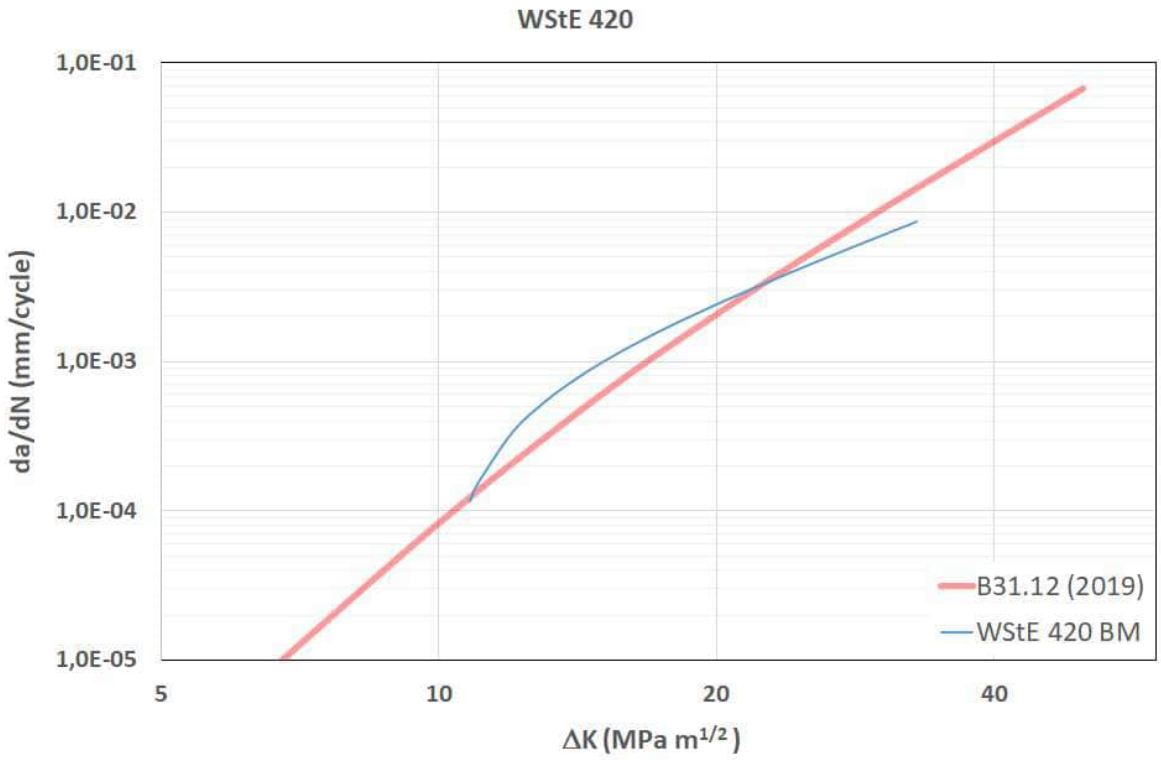


Figure 3.54: Crack growth WStE 420

3.16 St53.7

The samples were taken from a longitudinally submerged arc-welded pipe with a diameter of 770 mm and a wall thickness of 14.27 mm.

The base material has the following properties:

Table 3.49: Characteristics of St53.7

Production year	1972	
Production standard	DIN 17172	
Specific minimum characteristics	R_e [MPa]	363
	R_m [MPa]	510
	K_v /A [kgm/cm^2][11]	4
Material characteristics	R_e [MPa]	381
	R_m [MPa]	560
	K_v /A [kgm/cm^2][11]	8,8

Table 3.50: Chemical composition of St53.7

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.195	0.355	1.385	0.017	0.017			
	Ni	V	Ti	Nb				

Table 3.51: Fracture toughness of St53.7

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
St53.7	Base material	19	117.7
St53.7	Weld material	19	128.9

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- girth weld

[11] Notched-bar impact test as per DIN 50115; form DVM

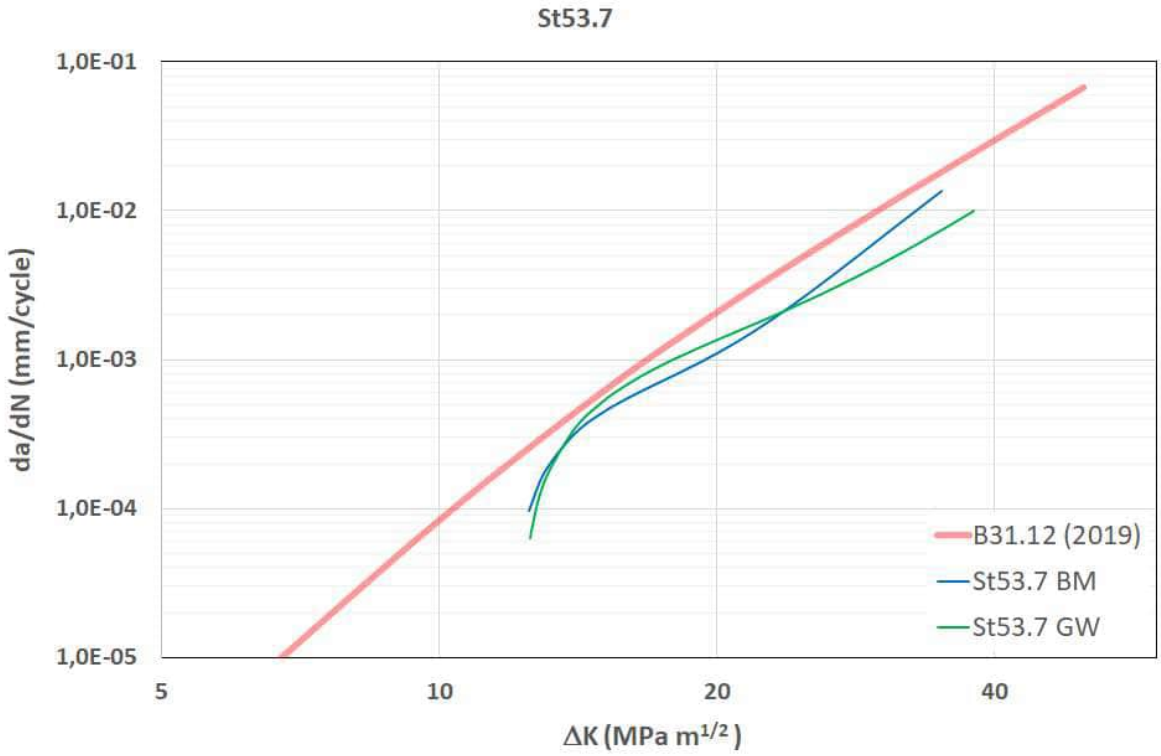
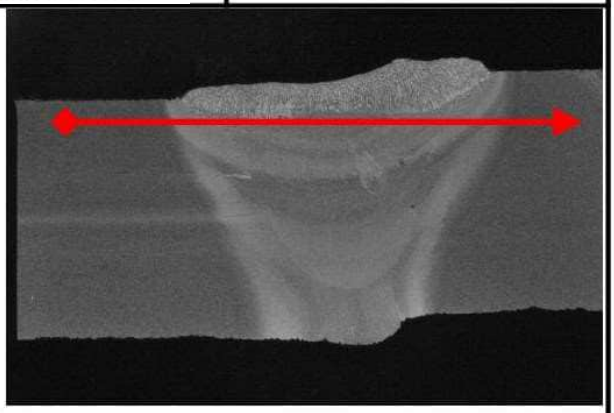


Figure 3.55: Crack growth St53.7

Hardness measurements were performed on two metallographic samples from item no. 19. The results of these hardness measurements are shown in Figures 3.56 to 3.59.

MPA STUTTGART	Test report MPAS-PPB 52310-08/1 Hardness test	Referat Metallographie und Elektronenmikroskopie

Order number 9039784000
Sample description 19.1; Outer layer
Administrator Silcher
Test instrument Zwick Z 323 (neu)
Serial number H2932-002-50430
Test conditions
☑ HV 10 DIN EN ISO 6507-1:2018-07
☐ HBW DIN EN ISO 6506-1:2015-02
☐ HRC DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	310,5	309,7	0,3101	193	185		BM 1
2	318,0	315,3	0,3166	185			
3	319,0	317,2	0,3181	183			
4	315,7	318,8	0,3173	184			
5	321,1	324,2	0,3227	178			
1	284,8	288,3	0,2865	226	223		HAZ 1
2	287,9	289,3	0,2886	223			
3	284,8	284,8	0,2848	229			
4	292,7	292,3	0,2925	217			
5	292,0	288,7	0,2904	220			
1	309,3	304,5	0,3069	197	192		WM
2	303,9	301,8	0,3028	202			
3	312,2	307,6	0,3099	193			
4	312,6	311,1	0,3119	191			
5	322,8	321,5	0,3221	179			
1	301,4	302,6	0,3020	203	220		HAZ 2
2	287,5	286,9	0,2872	225			
3	287,1	288,9	0,2880	224			
4	283,1	283,5	0,2833	231			
5	292,5	290,0	0,2912	219			
1	321,5	322,3	0,3219	179	181		BM 2
2	316,9	323,6	0,3203	181			
3	315,3	319,9	0,3176	184			
4	319,0	321,9	0,3205	181			
5	317,8	322,8	0,3203	181			

Date: 06.11.22
Tester: Scheck

Figure 3.56: Hardness measurements of St53.7 (1)

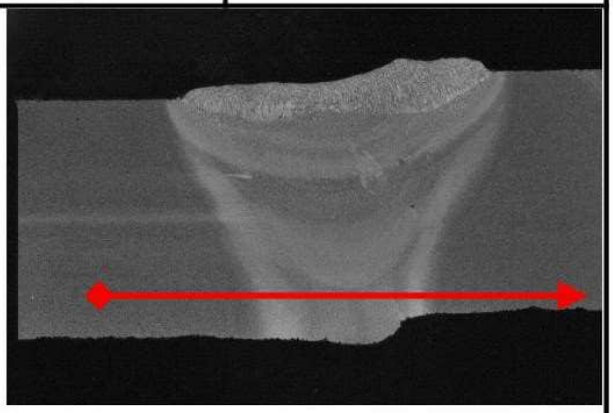
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	19.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑ HV	**10**	DIN EN ISO 6507-1:2018-07
☐ HBW		DIN EN ISO 6506-1:2015-02
☐ HRC		DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	320,9	318,4	0,3196	181	179		BM 1
2	318,8	321,9	0,3204	181			
3	320,7	323,4	0,3220	179			
4	321,5	325,0	0,3233	177			
5	324,4	323,6	0,3240	177			
1	334,8	337,7	0,3363	164	171		HAZ 1
2	327,9	323,0	0,3255	175			
3	330,6	327,3	0,3290	171			
4	330,0	328,2	0,3291	171			
5	327,9	326,3	0,3271	173			
1	315,1	312,8	0,3139	188	180		WM
2	319,0	316,5	0,3178	184			
3	325,7	321,5	0,3236	177			
4	324,0	323,2	0,3236	177			
5	329,2	327,9	0,3286	172			
1	329,4	329,2	0,3293	171	183		HAZ 2
2	321,1	320,3	0,3207	180			
3	315,7	314,5	0,3151	187			
4	317,0	312,8	0,3149	187			
5	311,8	309,5	0,3106	192			
1	323,8	325,1	0,3244	176	177		BM 2
2	323,2	328,2	0,3257	175			
3	323,2	325,0	0,3241	177			
4	319,6	325,5	0,3226	178			
5	313,8	327,9	0,3209	180			

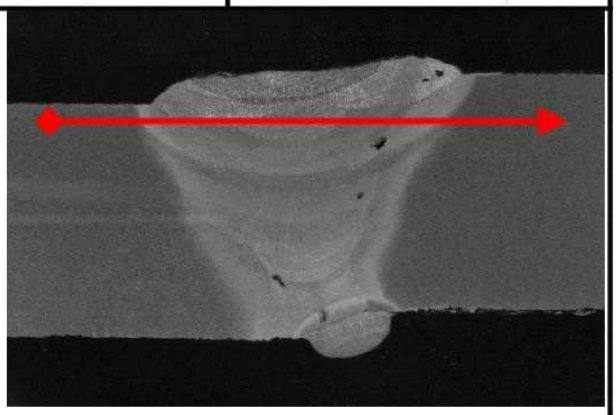
Date: 06.11.22

Tester: Scheck

Figure 3.57: Hardness measurements of X56.7 (2)

MPA	**Test report** MPAS-PPB 52310-08/1 Hardness test	**Referat** Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	19.2; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	312,0	314,7	0,3133	189	185		BM 1
2	311,8	317,8	0,3148	187			
3	313,8	319,0	0,3164	185			
4	318,2	318,8	0,3185	183			
5	320,7	320,1	0,3204	181			
1	317,8	317,8	0,3178	184	192		HAZ 1
2	302,2	305,3	0,3038	201			
3	307,2	307,6	0,3074	196			
4	311,3	310,5	0,3109	192			
5	314,9	314,7	0,3148	187			
1	321,1	322,8	0,3219	179	178		WM
2	322,1	320,7	0,3214	180			
3	340,0	332,7	0,3364	164			
4	317,6	316,5	0,3171	184			
5	317,6	315,9	0,3167	185			
1	296,2	296,2	0,2962	211	210		HAZ 2
2	294,8	294,9	0,2948	213			
3	294,7	295,4	0,2951	213			
4	300,8	298,5	0,2996	207			
5	298,7	299,3	0,2990	207			
1	320,9	329,4	0,3252	175	185		BM 2
2	313,4	320,7	0,3171	184			
3	312,6	318,2	0,3154	186			
4	309,7	316,1	0,3129	189			
5	308,0	313,2	0,3106	192			

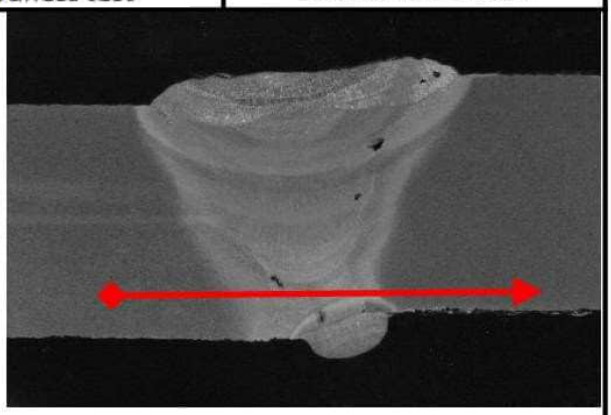
Date: 06.11.22

Tester: Scheck

Figure 3.58: Hardness measurements of X56.7 (3)

MPA STUTTGART	**Test report** MPAS-PPB 52310-08/1 Hardness test	**Referat** Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	19.2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	**d_1 µm**	**d_2 µm**	**d_m mm**	**Hardness HV**	**Mean value HV**	**Distance in mm**	**Remark**
1	319,0	321,1	0,3201	181	180		BM 1
2	318,4	321,7	0,3201	181			
3	322,4	320,7	0,3215	179			
4	317,8	320,1	0,3189	182			
5	325,2	326,5	0,3259	175			
1	315,3	312,4	0,3138	188	188		HAZ 1
2	312,4	311,3	0,3119	191			
3	316,1	312,8	0,3145	188			
4	314,3	313,8	0,3140	188			
5	315,9	318,0	0,3169	185			
1	306,6	303,5	0,3050	199	280		WM
2	303,7	297,4	0,3006	205			
3	296,2	290,6	0,2934	215			
4	220,3	216,9	0,2186	388			
5	217,0	218,0	0,2175	392			
1	312,8	314,9	0,3138	188	198		HAZ 2
2	313,6	308,0	0,3108	192			
3	303,9	305,5	0,3047	200			
4	299,3	297,2	0,2983	208			
5	304,3	302,2	0,3033	202			
1	312,4	316,1	0,3143	188	192		BM 2
2	314,2	317,8	0,3160	186			
3	305,3	313,4	0,3094	194			
4	302,2	304,9	0,3036	201			
5	308,2	312,2	0,3102	193			

Date: 06.11.22

Tester: Scheck

Figure 3.59: Hardness measurements of X56.7 (4)

3.17 X56.7

The samples were taken from a longitudinally welded pipe with a diameter of 914.4 mm and a wall thickness of 13.6 mm.

The relevant material-specific data is as follows:

Table 3.52: Characteristics of X56.7

Production year	1990	
Production standard	API STD 5 LX	
Specific minimum characteristics	R_e [MPa]	392
	R_m [MPa]	540
	K_v /A [kgm/cm^2]	4
Material characteristics	R_e [MPa]	486
	R_m [MPa]	615
	K_v [12] [J]	23

Table 3.53: Chemical composition of X56.7

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.2	0.32	1.36	0.03	0.02	0.09	0.08	0.01
	Ni	V	Ti	Nb				
	0.04	0.01	0.01	0.01				

Table 3.54: Fracture toughness of X56.7

Material	Ort	Item no.	K_{JIc} [MPa$\sqrt{m}$]
X56.7	Base material	12	99.6
X56.7	Weld material	12	122.5
X56.7	Weld material of the girth weld	12	132.4

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- longitudinal weld
- heat-affected zone (HAZ)

[12] Notched-bar impact test as per Charpy (EN ISO 148-1) at 0 °C

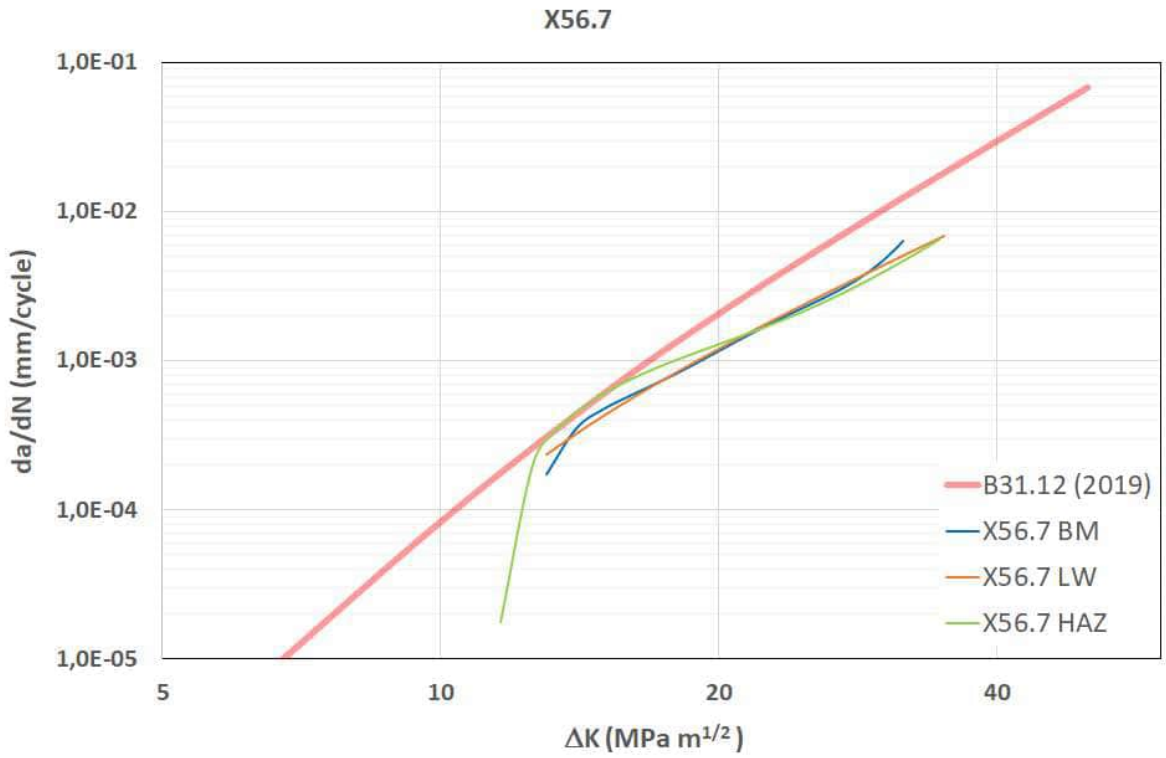


Figure 3.60: Crack growth X56.7

Hardness measurements were performed on four metallographic samples from item no. 12. The results of these hardness measurements are shown in Figures 3.61 to 3.70.

MPA STUTTGART

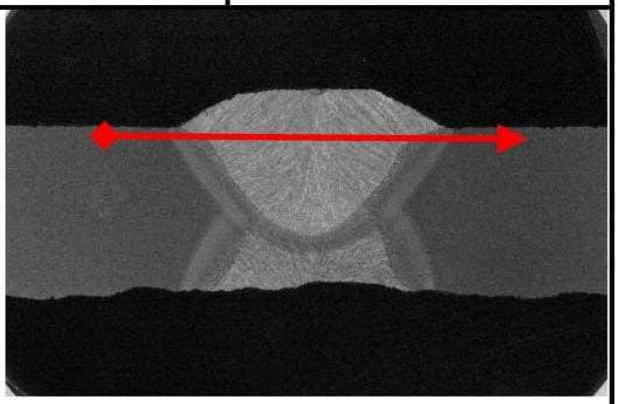
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.1-LN Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	296,2	293,1	0,2946	214	218		BM 1
2	293,1	292,9	0,2930	216			
3	288,5	288,9	0,2887	222			
4	288,8	292,1	0,2904	220			
5	292,7	292,2	0,2925	217			
1	272,7	270,9	0,2718	251	246		HAZ 1
2	275,3	274,6	0,2749	245			
3	268,8	269,2	0,2690	256			
4	279,8	277,5	0,2786	239			
5	280,2	276,3	0,2782	240			
1	275,6	273,8	0,2747	246	240		WM
2	277,3	278,8	0,2780	240			
3	279,4	280,6	0,2800	237			
4	279,0	275,4	0,2772	241			
5	279,8	280,4	0,2801	236			
1	268,6	267,1	0,2679	258	250		HAZ 2
2	270,5	273,6	0,2720	251			
3	273,8	273,6	0,2737	248			
4	270,2	275,0	0,2726	249			
5	274,2	276,3	0,2752	245			
1	292,9	294,1	0,2935	215	213		BM 2
2	294,8	296,2	0,2955	212			
3	291,6	293,5	0,2926	217			
4	295,4	296,6	0,2960	212			
5	299,9	297,2	0,2986	208			

Date: 06.11.22

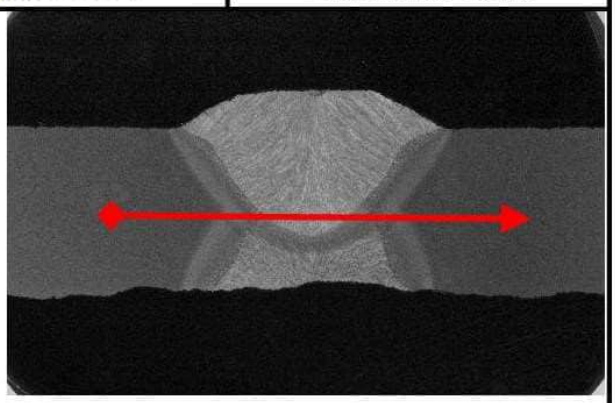
Tester: Scheck

Figure 3.61: Hardness measurements of X56.7 (1)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	12.1-LN Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	314,7	316,7	0,3157	186	191		BM 1
2	316,3	319,0	0,3177	184			
3	312,0	311,5	0,3118	191			
4	304,9	305,1	0,3050	199			
5	308,6	307,2	0,3079	196			
1	284,1	283,5	0,2838	230	223		HAZ 1
2	282,7	279,6	0,2811	235			
3	285,4	283,9	0,2847	229			
4	287,7	289,1	0,2884	223			
5	302,6	305,5	0,3041	201			
1	292,2	287,5	0,2899	221	214		WM
2	293,1	290,6	0,2918	218			
3	296,4	296,4	0,2964	211			
4	298,3	293,5	0,2959	212			
5	298,9	300,1	0,2995	207			
1	276,3	279,2	0,2777	240	231		HAZ 2
2	277,9	277,1	0,2775	241			
3	274,8	276,7	0,2758	244			
4	288,3	290,8	0,2895	221			
5	300,6	297,4	0,2990	207			
1	317,8	319,4	0,3186	183	188		BM 2
2	313,8	312,8	0,3133	189			
3	314,3	314,2	0,3143	188			
4	314,7	312,6	0,3136	189			
5	312,2	314,0	0,3131	189			

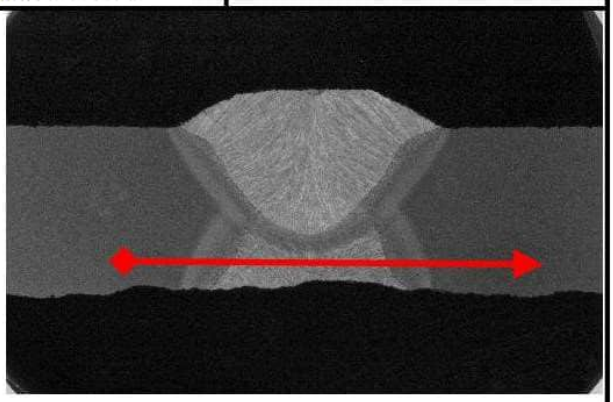
Date: 06.11.22

Tester: Scheck

Figure 3.62: Hardness measurements of X56.7 (2)

MPA STUTTGART	Test report MPAS-PPB 52310-08/1 Hardness test	Referat Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.1-LN Root
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	295,8	299,1	0,2974	210	212		BM 1
2	293,7	298,3	0,2960	212			
3	291,6	297,2	0,2944	214			
4	292,0	297,6	0,2948	213			
5	292,9	301,6	0,2972	210			
1	304,9	305,5	0,3052	199	220		HAZ 1
2	293,9	294,9	0,2944	214			
3	291,2	292,2	0,2917	218			
4	285,2	284,8	0,2850	228			
5	276,5	278,4	0,2774	241			
1	287,9	287,3	0,2876	224	228		WM
2	286,2	286,4	0,2863	226			
3	283,9	280,0	0,2820	233			
4	286,2	284,2	0,2852	228			
5	283,3	285,0	0,2842	230			
1	295,6	296,8	0,2962	211	224		HAZ 2
2	287,9	289,8	0,2888	222			
3	286,2	287,5	0,2869	225			
4	285,2	284,6	0,2849	228			
5	282,9	281,5	0,2822	233			
1	299,7	302,4	0,3011	205	209		BM 2
2	293,5	298,9	0,2962	211			
3	292,5	296,2	0,2943	214			
4	296,8	297,4	0,2971	210			
5	298,3	305,1	0,3017	204			

Date: 06.11.22

Tester: Scheck

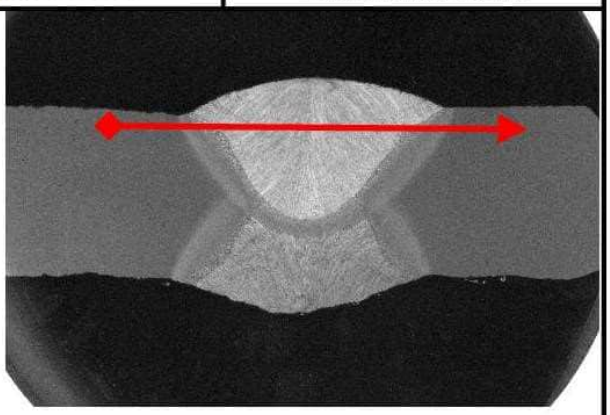
Figure 3.63: Hardness measurements of X56.7 (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.2-LN Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	302,8	296,8	0,2998	206	210		BM 1
2	297,6	298,1	0,2979	209			
3	299,7	295,6	0,2976	209			
4	297,5	294,1	0,2958	212			
5	294,7	294,9	0,2948	213			
1	281,0	277,5	0,2793	238	237		HAZ 1
2	282,9	274,2	0,2786	239			
3	276,9	278,1	0,2775	241			
4	282,9	281,3	0,2821	233			
5	281,7	279,6	0,2806	235			
1	282,1	280,8	0,2815	234	231		WM
2	285,8	281,9	0,2838	230			
3	286,6	284,4	0,2855	227			
4	282,3	282,7	0,2825	232			
5	285,2	282,7	0,2840	230			
1	289,8	292,2	0,2910	219	233		HAZ 2
2	280,8	277,3	0,2791	238			
3	283,1	278,5	0,2808	235			
4	280,0	282,1	0,2810	235			
5	280,6	277,1	0,2789	238			
1	304,1	304,1	0,3041	201	204		BM 2
2	298,9	297,4	0,2982	209			
3	302,2	300,5	0,3014	204			
4	301,4	301,0	0,3012	204			
5	302,0	302,4	0,3022	203			

Date: 06.11.22

Tester: Scheck

Figure 3.64: Hardness measurements of X56.7 (4)

MPA STUTTGART

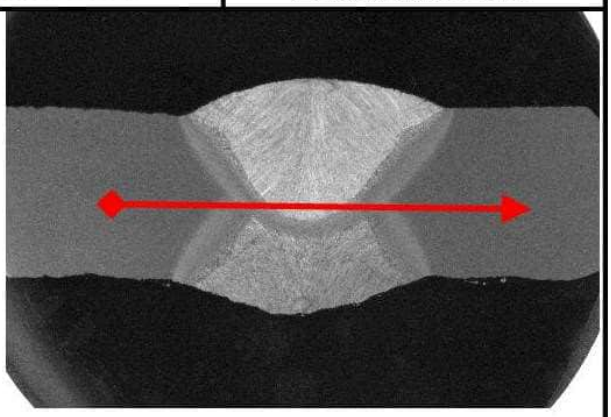
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.2-LN Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV 10 — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	315,1	317,8	0,3164	185	188		BM 1
2	318,4	314,9	0,3166	185			
3	313,2	311,1	0,3122	190			
4	313,0	312,6	0,3128	190			
5	311,3	309,5	0,3104	192			
1	282,1	279,6	0,2808	235	215		HAZ 1
2	284,8	285,4	0,2851	228			
3	288,9	287,9	0,2884	223			
4	307,2	305,1	0,3062	198			
5	308,6	310,3	0,3095	194			
1	288,3	286,6	0,2875	224	214		WM
2	290,6	288,3	0,2895	221			
3	292,5	287,9	0,2902	220			
4	302,6	299,7	0,3012	204			
5	302,6	304,1	0,3034	202			
1	285,6	283,3	0,2845	229	220		HAZ 2
2	285,0	285,8	0,2854	228			
3	286,4	285,6	0,2860	227			
4	298,9	296,4	0,2976	209			
5	300,1	299,3	0,2997	206			
1	320,7	321,1	0,3209	180	187		BM 2
2	318,8	316,5	0,3177	184			
3	315,5	312,6	0,3140	188			
4	309,3	309,3	0,3093	194			
5	313,8	312,8	0,3133	189			

Date: 06.11.22

Tester: Scheck

Figure 3.65: Hardness measurements of X56.7 (5)

MPA STUTTGART

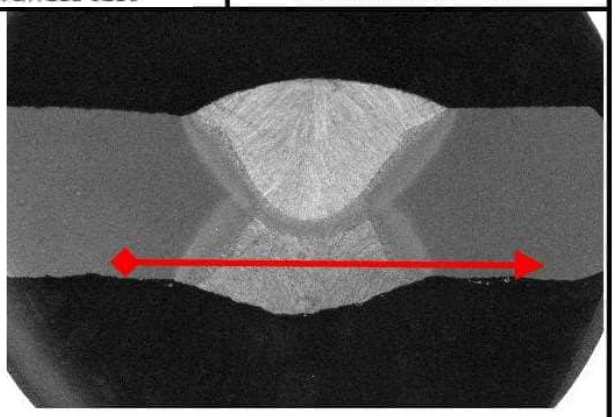
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.2-LN Root
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV 10 — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	301,6	300,5	0,3011	205	206		BM 1
2	302,0	303,9	0,3029	202			
3	296,4	300,8	0,2986	208			
4	297,6	302,6	0,3001	206			
5	297,2	300,6	0,2989	208			
1	289,1	286,2	0,2877	224	215		HAZ 1
2	286,4	289,8	0,2881	223			
3	294,9	292,9	0,2939	215			
4	293,9	299,1	0,2965	211			
5	304,5	302,8	0,3037	201			
1	300,1	302,4	0,3013	204	202		WM
2	302,2	302,8	0,3025	203			
3	300,1	299,9	0,3000	206			
4	308,2	306,4	0,3073	196			
5	304,9	304,1	0,3045	200			
1	307,6	306,4	0,3070	197	209		HAZ 2
2	299,3	295,6	0,2974	210			
3	297,0	298,1	0,2975	209			
4	294,5	292,9	0,2937	215			
5	293,9	291,6	0,2928	216			
1	310,3	310,7	0,3105	192	201		BM 2
2	304,1	307,4	0,3057	198			
3	300,8	302,2	0,3015	204			
4	299,3	301,8	0,3006	205			
5	298,5	301,4	0,2999	206			

Date: 06.11.22

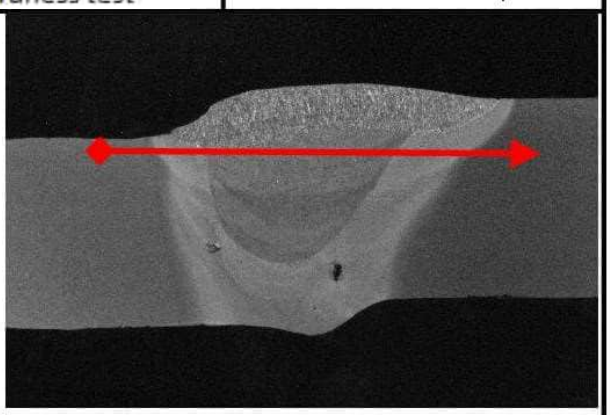
Tester: Scheck

Figure 3.66: Hardness measurements of X56.7 (6)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	12.1-UN Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	305,3	308,4	0,3069	197	197		BM 1
2	305,7	308,6	0,3072	197			
3	304,7	305,1	0,3049	199			
4	306,4	310,1	0,3082	195			
5	305,7	309,7	0,3077	196			
1	296,4	295,8	0,2961	212	221		HAZ 1
2	285,0	286,9	0,2859	227			
3	284,0	292,0	0,2880	224			
4	287,6	285,8	0,2867	226			
5	294,3	294,2	0,2943	214			
1	308,0	303,0	0,3055	199	188		WM
2	305,9	304,7	0,3053	199			
3	314,5	315,7	0,3151	187			
4	314,1	314,7	0,3144	188			
5	332,3	331,5	0,3319	168			
1	291,0	287,7	0,2894	221	222		HAZ 2
2	286,6	291,4	0,2890	222			
3	286,9	287,7	0,2873	225			
4	290,6	291,6	0,2911	219			
5	289,6	287,3	0,2884	223			
1	304,3	312,6	0,3084	195	196		BM 2
2	306,3	314,5	0,3104	192			
3	303,7	312,6	0,3081	195			
4	304,1	306,8	0,3054	199			
5	302,0	310,3	0,3062	198			

Date: 06.11.22

Tester: Scheck

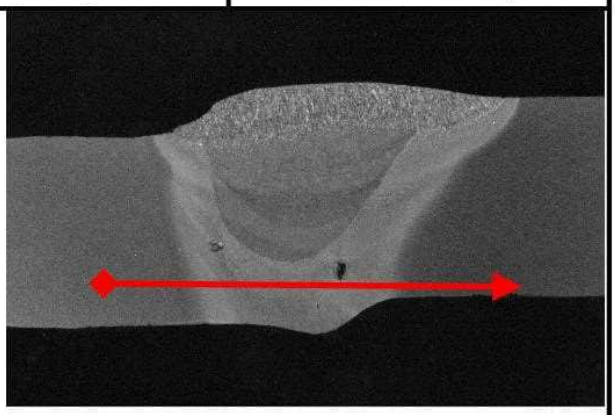
Figure 3.67: Hardness measurements of X56.7 (7)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.1-UN **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	303,9	309,5	0,3067	197	194		BM 1
2	303,7	307,6	0,3056	199			
3	305,1	310,1	0,3076	196			
4	309,1	312,2	0,3106	192			
5	313,6	317,6	0,3156	186			
1	317,4	316,3	0,3169	185	179		HAZ 1
2	318,4	319,0	0,3187	183			
3	324,2	323,2	0,3237	177			
4	322,3	323,6	0,3230	178			
5	328,2	331,1	0,3296	171			
1	313,4	311,3	0,3124	190	180		WM
2	315,3	312,8	0,3140	188			
3	326,5	326,1	0,3263	174			
4	320,1	317,6	0,3188	182			
5	337,3	334,8	0,3360	164			
1	335,4	340,2	0,3378	163	174		HAZ 2
2	322,3	326,3	0,3243	176			
3	313,6	323,0	0,3183	183			
4	322,1	329,6	0,3259	175			
5	320,5	330,0	0,3252	175			
1	316,3	324,4	0,3204	181	184		BM 2
2	314,2	322,6	0,3184	183			
3	314,5	323,4	0,3189	182			
4	314,0	320,3	0,3172	184			
5	308,4	319,7	0,3140	188			

Date: 06.11.22

Tester: Scheck

Figure 3.68: Hardness measurements of X56.7 (8)

MPA STUTTGART

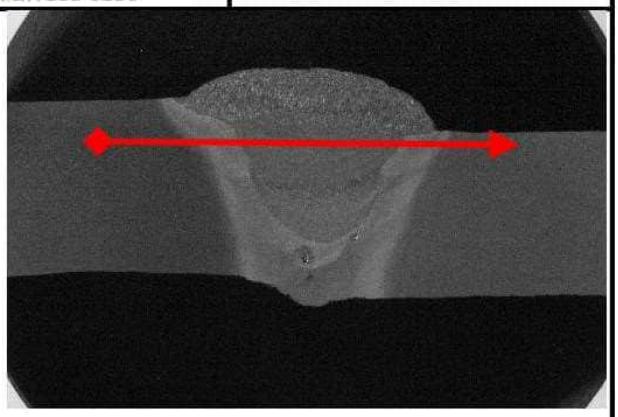
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	12.2-UN Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	313,0	319,3	0,3161	186	192		BM 1
2	310,1	313,6	0,3119	191			
3	305,7	309,7	0,3077	196			
4	305,5	313,8	0,3097	193			
5	308,0	310,5	0,3093	194			
1	291,4	293,3	0,2924	217	226		HAZ 1
2	285,8	286,2	0,2860	227			
3	284,4	286,4	0,2854	228			
4	280,6	286,9	0,2838	230			
5	284,4	284,6	0,2845	229			
1	315,7	320,3	0,3180	183	190		WM
2	316,5	312,6	0,3146	187			
3	310,1	300,5	0,3053	199			
4	312,2	307,8	0,3100	193			
5	316,5	313,2	0,3149	187			
1	300,5	297,8	0,2992	207	218		HAZ 2
2	289,3	288,1	0,2887	222			
3	281,9	281,7	0,2818	234			
4	290,4	288,3	0,2893	222			
5	299,3	299,1	0,2992	207			
1	315,1	316,3	0,3157	186	191		BM 2
2	312,8	316,7	0,3148	187			
3	310,3	309,9	0,3101	193			
4	310,1	311,1	0,3106	192			
5	304,3	309,3	0,3068	197			

Date: 06.11.22

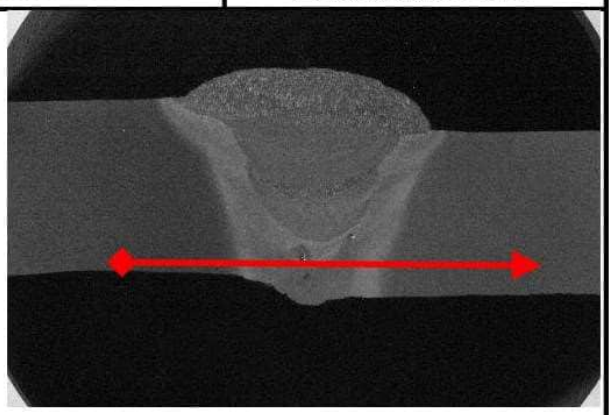
Tester: Scheck

Figure 3.69: Hardness measurements of X56.7 (9)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	12.2-UN Root
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	315,2	326,3	0,3207	180	187		BM 1
2	309,7	320,9	0,3153	187			
3	313,2	316,9	0,3151	187			
4	306,6	315,1	0,3108	192			
5	309,1	316,5	0,3128	190			
1	314,7	318,6	0,3166	185	185		HAZ 1
2	318,2	314,9	0,3165	185			
3	318,0	316,1	0,3171	184			
4	318,0	316,7	0,3174	184			
5	319,0	314,0	0,3165	185			
1	326,9	325,0	0,3260	175	178		WM
2	313,4	314,0	0,3137	188			
3	318,4	315,3	0,3168	185			
4	332,1	330,2	0,3312	169			
5	331,3	328,4	0,3298	170			
1	320,7	318,8	0,3197	181	182		HAZ 2
2	320,1	318,8	0,3194	182			
3	320,1	317,8	0,3189	182			
4	320,5	320,3	0,3204	181			
5	318,2	318,0	0,3181	183			
1	315,9	319,9	0,3179	184	190		BM 2
2	313,6	317,4	0,3155	186			
3	311,6	316,1	0,3139	188			
4	307,8	312,2	0,3100	193			
5	303,5	309,7	0,3066	197			

Date: 06.11.22

Tester: Scheck

Figure 3.70: Hardness measurements of X56.7 (10)

3.18 St60.7

The samples were taken from a spiral welded pipe with a diameter of 950 mm and a wall thickness of 13 mm.

The base material has the following properties:

Table 3.55: Characteristics of St60.7

Production year	1973	
Production standard	DIN 17172 / DIN 2470	
Specific minimum characteristics	R_e [MPa]	412
	R_m [MPa]	549
	K_v /A [kgm/cm^2]	4
Material characteristics	R_e [MPa]	517
	R_m [MPa]	663
	K_v /A [kgm/cm^2][13]	6.7

Table 3.56: Chemical composition of St60.7

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.17	0.29	1.39	0.02	0.011			
	Ni	V	Ti	Nb				
		0.06						

Table 3.57: Fracture toughness of St60.7

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
St60.7	Base material	6	148.1
St60.7	Weld material	6	129.8

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material

[13] Notched-bar impact testing as per DIN 50115; notch form: DVM; temperature: 0 °C

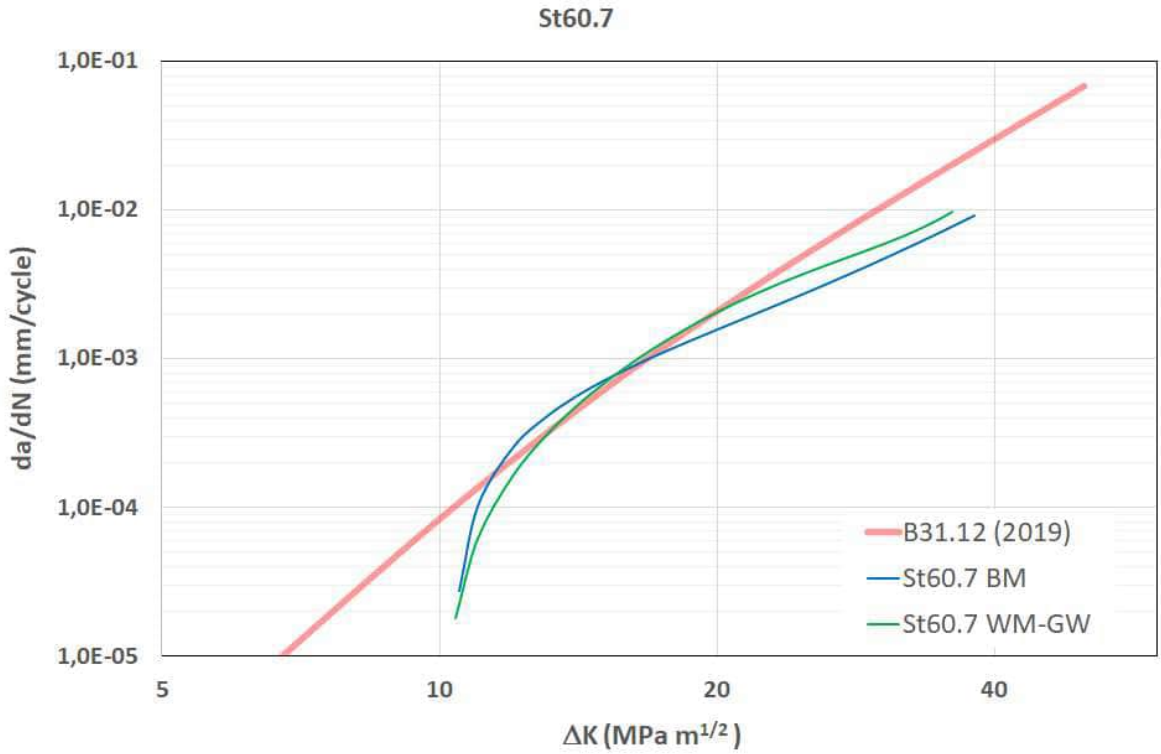


Figure 3.71: Crack growth St60.7

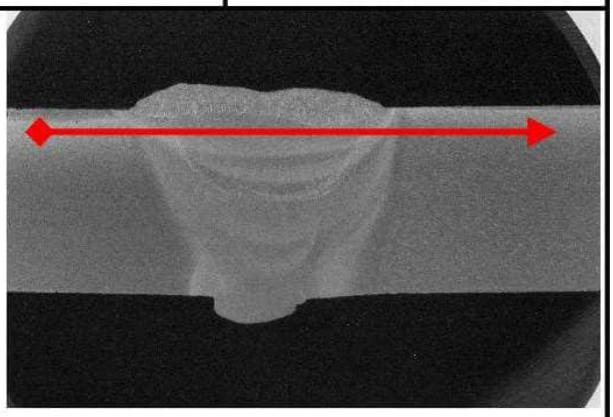
Hardness measurements were performed on two metallographic samples from item no. 6. The results of these hardness measurements are shown in Figures 3.72 to 3.75.

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	6.1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	269,2	271,9	0,2706	253	244		BM 1
2	275,0	274,8	0,2749	245			
3	273,6	276,5	0,2750	245			
4	276,3	277,9	0,2771	242			
5	279,6	279,0	0,2793	238			
1	258,4	258,8	0,2586	277	279		HAZ 1
2	249,9	254,5	0,2522	292			
3	245,4	262,7	0,2540	287			
4	251,8	254,0	0,2529	290			
5	271,9	272,1	0,2720	251			
1	302,8	305,0	0,3039	201	187		WM
2	326,3	323,8	0,3250	176			
3	320,3	320,1	0,3202	181			
4	307,4	305,1	0,3063	198			
5	323,8	323,0	0,3234	177			
1	312,2	310,7	0,3114	191	208		HAZ 2
2	302,0	301,0	0,3015	204			
3	296,8	296,8	0,2968	210			
4	293,1	294,5	0,2938	215			
5	291,2	288,5	0,2899	221			
1	292,0	292,5	0,2923	217	221		BM 2
2	290,0	288,9	0,2894	221			
3	288,5	287,1	0,2878	224			
4	289,8	288,9	0,2893	221			
5	288,1	292,2	0,2902	220			

Date: 06.11.22

Tester: Scheck

Figure 3.72: Hardness measurements of St60.7 (1)

MPA STUTTGART

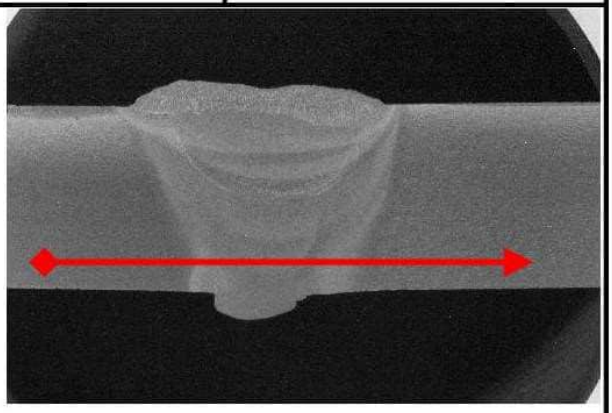
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	6.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV **10**	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	280,0	286,0	0,2830	232	229		BM 1
2	279,6	280,0	0,2798	237			
3	280,8	283,3	0,2821	233			
4	284,2	290,2	0,2872	225			
5	288,3	294,3	0,2913	219			
1	304,5	306,8	0,3056	199	201		HAZ 1
2	301,0	302,6	0,3018	204			
3	302,6	303,9	0,3033	202			
4	302,0	302,8	0,3024	203			
5	305,7	306,4	0,3061	198			
1	316,1	318,0	0,3170	184	179		WM
2	312,6	310,7	0,3117	191			
3	327,3	327,5	0,3274	173			
4	329,2	326,7	0,3279	172			
5	326,9	328,6	0,3277	173			
1	312,6	313,4	0,3130	189	199		HAZ 2
2	307,6	306,6	0,3071	197			
3	302,4	299,9	0,3012	204			
4	301,4	302,0	0,3017	204			
5	305,7	304,7	0,3052	199			
1	294,7	295,4	0,2951	213	216		BM 2
2	294,7	294,9	0,2948	213			
3	290,0	293,5	0,2917	218			
4	291,4	293,5	0,2925	217			
5	290,8	293,3	0,2920	217			

Date: 06.11.22

Tester: Scheck

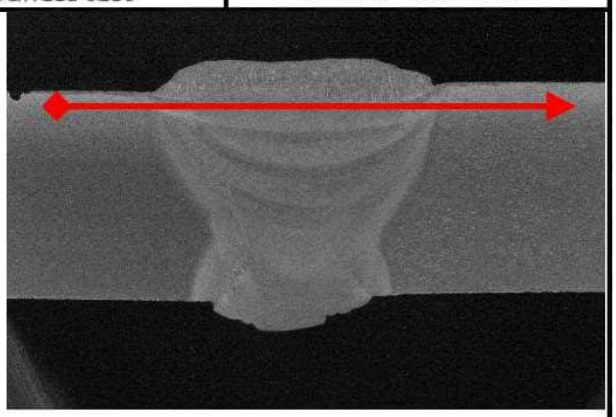
Figure 3.73: Hardness measurements of St60.7 (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	6.2; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	279,0	280,4	0,2797	237	233		BM 1
2	281,2	283,5	0,2824	233			
3	280,0	280,4	0,2802	236			
4	284,0	284,6	0,2843	229			
5	284,0	285,4	0,2847	229			
1	252,8	255,5	0,2542	287	267		HAZ 1
2	241,2	244,1	0,2426	315			
3	252,2	256,4	0,2543	287			
4	275,4	276,7	0,2761	243			
5	305,5	302,0	0,3038	201			
1	313,8	312,2	0,3130	189	189		WM
2	320,9	319,2	0,3201	181			
3	312,4	310,3	0,3113	191			
4	311,1	309,1	0,3101	193			
5	314,3	312,0	0,3131	189			
1	269,0	269,4	0,2692	256	245		HAZ 2
2	295,1	252,2	0,2736	248			
3	254,7	253,6	0,2542	287			
4	294,5	290,0	0,2923	217			
5	292,2	292,5	0,2923	217			
1	285,0	286,0	0,2855	228	229		BM 2
2	285,6	286,2	0,2859	227			
3	282,1	285,4	0,2837	230			
4	278,6	278,3	0,2784	239			
5	289,8	287,5	0,2886	223			

Date: 06.11.22

Tester: Scheck

Figure 3.74: Hardness measurements of St60.7 (3)

MPA STUTTGART

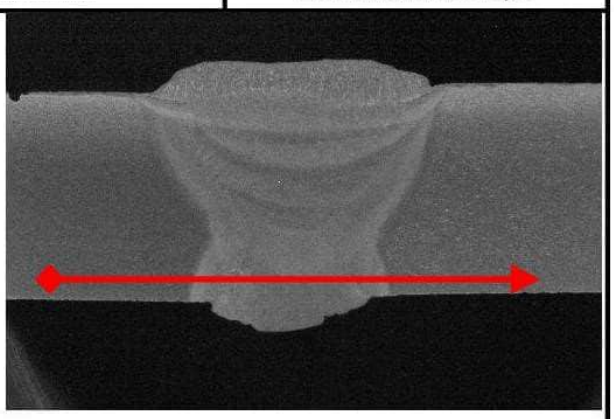
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	6.2; Root
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV 10 — DIN EN ISO 6507-1:2018-07
- ☐ HBW — DIN EN ISO 6506-1:2015-02
- ☐ HRC — DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	280,8	284,1	0,2825	232	223		BM 1
2	287,7	288,7	0,2882	223			
3	284,2	292,0	0,2881	223			
4	288,7	291,6	0,2902	220			
5	291,8	293,1	0,2925	217			
1	287,3	287,3	0,2873	225	212		HAZ 1
2	292,3	294,1	0,2932	216			
3	300,6	299,7	0,3001	206			
4	297,9	298,5	0,2982	209			
5	303,7	302,4	0,3030	202			
1	320,5	318,4	0,3194	182	183		WM
2	331,9	329,2	0,3305	170			
3	323,2	322,6	0,3229	178			
4	311,3	309,1	0,3102	193			
5	311,1	310,1	0,3106	192			
1	310,7	310,5	0,3106	192	192		HAZ 2
2	305,1	305,5	0,3053	199			
3	309,9	309,3	0,3096	193			
4	312,6	311,3	0,3120	191			
5	314,5	316,1	0,3153	187			
1	292,1	296,6	0,2943	214	217		BM 2
2	291,2	292,2	0,2917	218			
3	291,0	292,7	0,2918	218			
4	290,6	295,6	0,2931	216			
5	288,5	292,7	0,2906	220			

Date: 06.11.22

Tester: Scheck

Figure 3.75: Hardness measurements of St60.7 (4)

3.19 P460 NH

The samples were taken from a pipe-shaped sleeve with a diameter of 700 mm and a wall thickness of 20 mm.

The relevant material-specific data is as follows:

Table 3.58: Characteristics P460 NH

Production year	2017	
Production standard	DIN EN 10028-3	
Specific minimum characteristics	R_e [MPa]	445
	R_m [MPa]	570
	K_v [J]	40
Material characteristics	R_e [MPa]	488
	R_m [MPa]	652
	K_v [14][J]	80

Table 3.59: Chemical composition of P460 NH

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.177	0.253	1.508	0.013	0.009	0.018	0.046	0.012
	Ni	V	Ti	Nb				
	0.024	0.143	0.002	0.001				

Table 3.60: Fracture toughness of P460 NH

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
P460 NH	Base material	8	104.1
P460 NH	Weld material	8	154.9

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- longitudinal weld

[14] Notched-bar impact test as per DIN EN 10045, V-notch, transverse

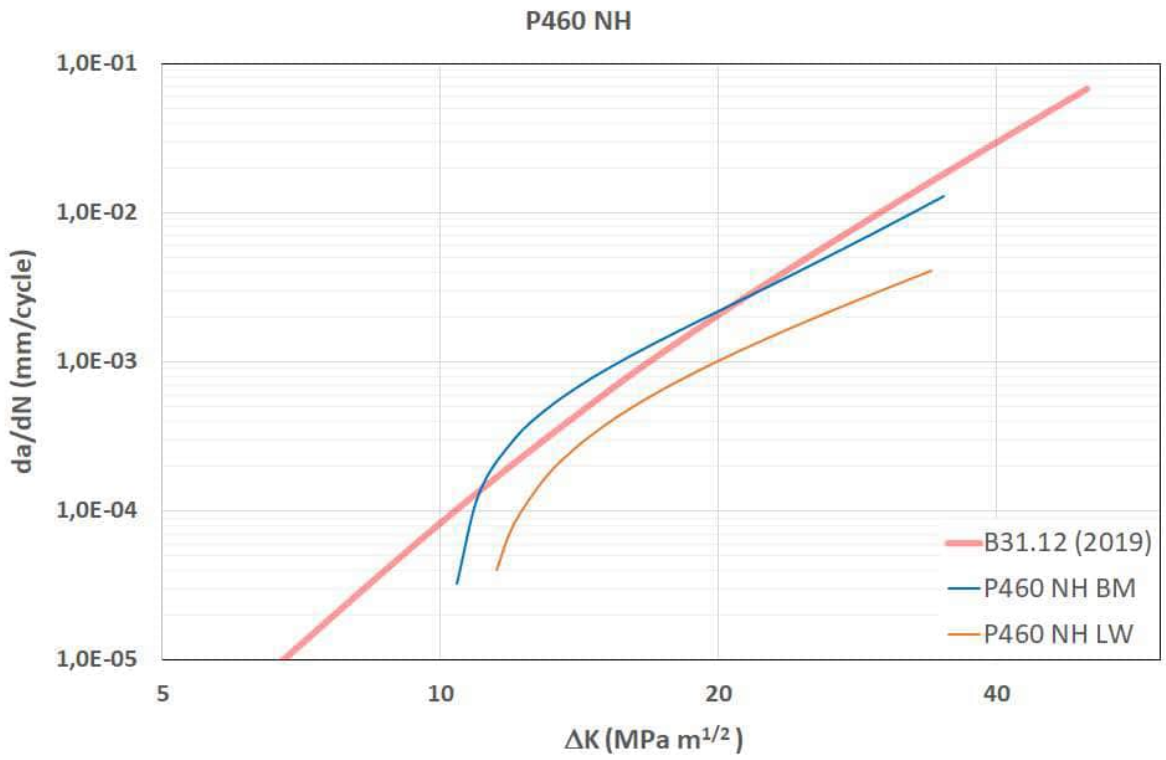


Figure 3.76: Crack growth P460 NH

Hardness measurements were performed on two metallographic samples from item no. 8. The results of these hardness measurements are shown in Figures 3.77 to 3.81.

MPA STUTTGART

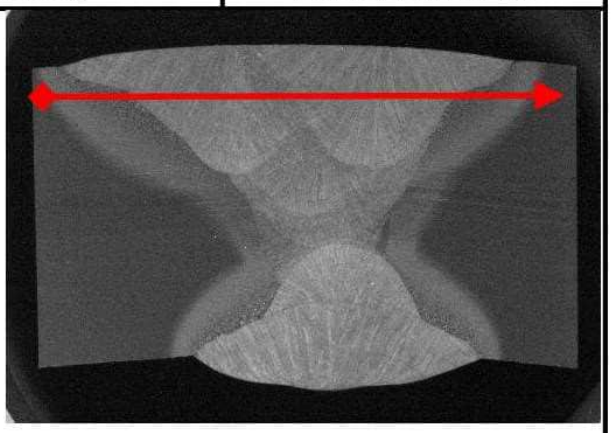
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	8.1; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	299,9	302,6	0,3013	204	206		BM 1
2	301,0	304,7	0,3028	202			
3	302,2	307,8	0,3050	199			
4	293,1	298,9	0,2960	212			
5	292,5	298,5	0,2955	212			
1	269,4	270,5	0,2699	254	255		HAZ 1
2	269,2	270,1	0,2696	255			
3	270,2	268,8	0,2695	255			
4	271,9	268,6	0,2703	254			
5	268,8	269,4	0,2691	256			
1	278,6	275,2	0,2769	242	242		WM
2	281,3	276,7	0,2790	238			
3	275,4	275,2	0,2753	245			
4	276,1	275,6	0,2759	244			
5	280,2	276,9	0,2785	239			
1	266,1	266,5	0,2663	261	261		HAZ 2
2	264,6	267,3	0,2660	262			
3	266,9	269,6	0,2683	258			
4	263,6	269,4	0,2665	261			
5	265,5	265,7	0,2656	263			
1	310,5	313,8	0,3122	190	198		BM 2
2	307,0	310,5	0,3088	195			
3	304,3	309,1	0,3067	197			
4	300,5	302,6	0,3016	204			
5	299,5	304,1	0,3018	204			

Date: 06.11.22

Tester: Scheck

Figure 3.77: Hardness measurements of P460 NH (1)

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Hardness test

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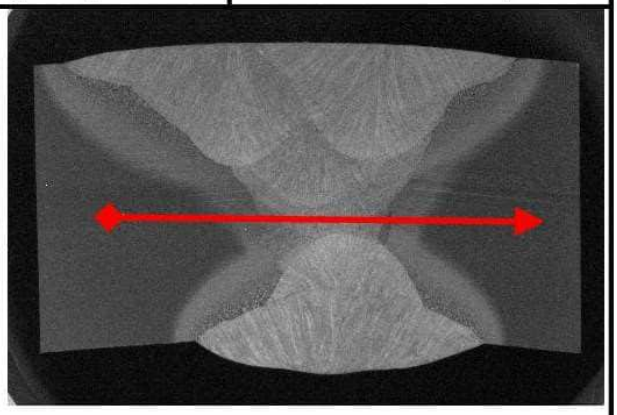

Order number	9039784000
Sample description	8.1; Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	299,9	299,1	0,2995	207	206		BM 1
2	299,3	300,2	0,2997	206			
3	298,7	302,4	0,3006	205			
4	296,6	302,4	0,2995	207			
5	301,2	303,3	0,3022	203			
1	285,0	280,6	0,2828	232	233		HAZ 1
2	292,3	291,4	0,2918	218			
3	282,3	283,9	0,2831	231			
4	286,9	283,9	0,2854	228			
5	269,8	268,4	0,2691	256			
1	291,4	289,3	0,2904	220	230		WM
2	279,4	277,7	0,2786	239			
3	288,7	284,2	0,2864	226			
4	287,9	284,4	0,2861	227			
5	281,5	279,0	0,2802	236			
1	274,2	276,7	0,2754	244	224		HAZ 2
2	308,9	309,3	0,3091	194			
3	294,1	288,9	0,2915	218			
4	303,7	301,6	0,3026	202			
5	267,1	266,9	0,2670	260			
1	301,4	306,4	0,3039	201	202		BM 2
2	297,2	299,9	0,2986	208			
3	302,0	305,9	0,3040	201			
4	301,4	307,0	0,3042	200			
5	304,9	306,8	0,3058	198			

Date: 06.11.22

Tester: Scheck

Figure 3.78: Hardness measurements of P460 NH (2)

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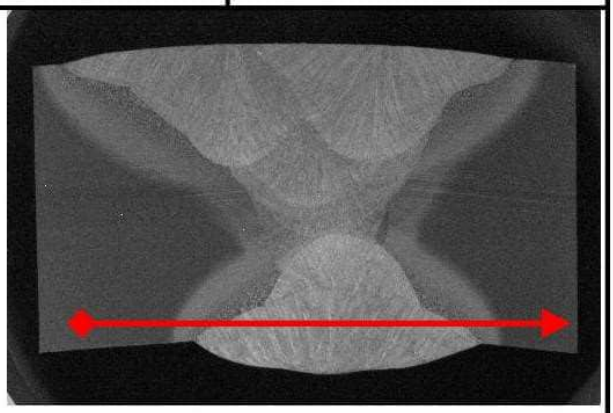
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	8.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV **10**	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	292,9	300,1	0,2965	211	205		BM 1
2	299,1	302,8	0,3010	205			
3	299,7	305,7	0,3027	202			
4	304,1	306,2	0,3051	199			
5	297,0	302,0	0,2995	207			
1	261,9	260,5	0,2612	272	276		HAZ 1
2	259,3	262,4	0,2608	273			
3	260,9	258,4	0,2597	275			
4	257,4	251,2	0,2543	287			
5	259,0	260,7	0,2599	275			
1	276,3	273,4	0,2748	246	242		WM
2	279,8	276,5	0,2781	240			
3	278,3	276,1	0,2772	241			
4	275,8	277,3	0,2766	242			
5	278,1	277,3	0,2777	240			
1	263,8	265,7	0,2647	265	270		HAZ 2
2	259,3	263,8	0,2615	271			
3	257,8	258,0	0,2579	279			
4	259,7	262,1	0,2609	272			
5	264,6	264,6	0,2646	265			
1	303,5	308,2	0,3058	198	198		BM 2
2	302,8	309,1	0,3060	198			
3	300,6	305,3	0,3029	202			
4	303,9	310,7	0,3073	196			
5	305,9	310,3	0,3081	195			

Date: 06.11.22

Tester: Scheck

Figure 3.79: Hardness measurements of P460 NH (3)

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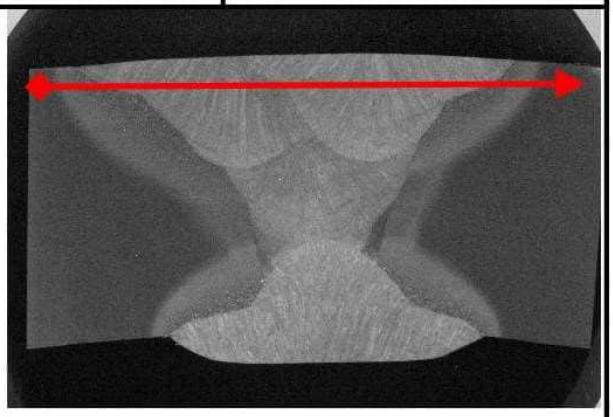
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	8.2; Outer layer
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

☑	HV 10	DIN EN ISO 6507-1:2018-07
☐	HBW	DIN EN ISO 6506-1:2015-02
☐	HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	291,0	292,5	0,2917	218	218		BM 1
2	296,6	299,7	0,2982	209			
3	290,2	294,1	0,2921	217			
4	287,1	291,2	0,2891	222			
5	286,0	289,3	0,2877	224			
1	269,4	269,2	0,2693	256	253		HAZ 1
2	271,7	269,6	0,2707	253			
3	274,0	271,9	0,2730	249			
4	277,9	267,1	0,2725	250			
5	266,7	271,3	0,2690	256			
1	279,2	277,3	0,2782	240	242		WM
2	282,7	277,1	0,2799	237			
3	276,7	275,0	0,2758	244			
4	275,0	274,0	0,2745	246			
5	275,2	275,4	0,2753	245			
1	271,5	272,7	0,2721	250	256		HAZ 2
2	269,2	266,3	0,2678	259			
3	269,2	266,5	0,2679	258			
4	266,7	263,4	0,2651	264			
5	274,0	273,8	0,2739	247			
1	308,9	310,5	0,3097	193	203		BM 2
2	309,5	311,5	0,3105	192			
3	293,1	299,5	0,2963	211			
4	298,3	305,3	0,3018	204			
5	292,0	297,8	0,2949	213			

Date: 06.11.22

Tester: Scheck

Figure 3.80: Hardness measurements of P460 NH (4)

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Test report
MPAS-PPB 52310-08/1
Hardness test

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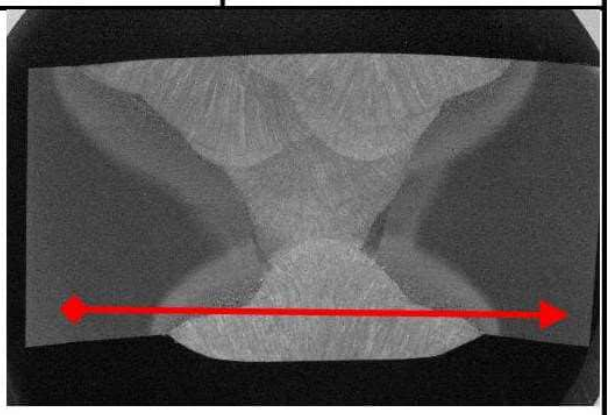


Order number	9039784000
Sample description	8.2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430

Test conditions

- ☑ HV **10** DIN EN ISO 6507-1:2018-07
- ☐ HBW DIN EN ISO 6506-1:2015-02
- ☐ HRC DIN EN ISO 6508-1:2016-12
- ☐ Test temperatur, if outside (23+/-5) °C

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	300,1	304,9	0,3025	203	204		BM 1
2	299,7	303,0	0,3014	204			
3	300,1	303,0	0,3016	204			
4	303,2	305,3	0,3043	200			
5	298,7	300,3	0,2995	207			
1	265,9	269,6	0,2678	259	269		HAZ 1
2	265,3	265,5	0,2654	263			
3	260,3	260,9	0,2606	273			
4	256,6	256,8	0,2567	281			
5	263,2	263,6	0,2634	267			
1	284,0	277,5	0,2807	235	235		WM
2	279,4	282,5	0,2809	235			
3	281,9	279,0	0,2804	236			
4	281,7	282,3	0,2820	233			
5	280,2	278,5	0,2794	238			
1	264,2	266,7	0,2655	263	266		HAZ 2
2	262,0	266,9	0,2644	265			
3	258,4	258,8	0,2586	277			
4	267,8	266,1	0,2669	260			
5	263,6	266,5	0,2651	264			
1	294,3	304,5	0,2994	207	207		BM 2
2	295,4	304,1	0,2997	206			
3	295,2	299,9	0,2975	209			
4	294,3	301,6	0,2980	209			
5	301,2	305,1	0,3031	202			

Date: 06.11.22

Tester: Scheck

Figure 3.81: Hardness measurements of P460 NH (5)

3.20 X70

The samples were taken from a spiral welded pipe with a diameter of 1100 mm and a wall thickness of 15 mm.

The relevant material-specific data is as follows:

Table 3.61: Characteristics of X70

Production year	1974	
Production standard	DIN 2470/2 / DIN 17172 / Ruhrgas Standard RN 4205	
Specific minimum characteristics	R_e [MPa]	491
	R_m [MPa]	598
	K_v /A [kgm/cm^2]	4
Material characteristics	R_e [MPa]	517
	R_m [MPa]	648
	K_v /A [kgm/cm^2][15]	7.1

Table 3.62: Chemical composition of X70

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.12	0.25	1.56	0.02	0.009			
	Ni	V	Ti	Nb				
		0.05		0.049				

Table 3.63: Fracture toughness of X70

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
X70	Base material	11	122.5
X70	Weld material	11	94.9
X70	Heat-affected zone	11	88.6
X70	Base material	4	81.8
X70	Weld material	4	103.0
X70	Heat-affected zone	4	76.0

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5. Item no. 4 (spiral weld area) and item no. 11 (girth weld area) were investigated.

Samples were taken from the following areas:

- base material
- weld material (WM)
- heat-affected zone

[15] Transverse notched-bar impact test, sample form DVM, as per DIN 50115, at 0 °C

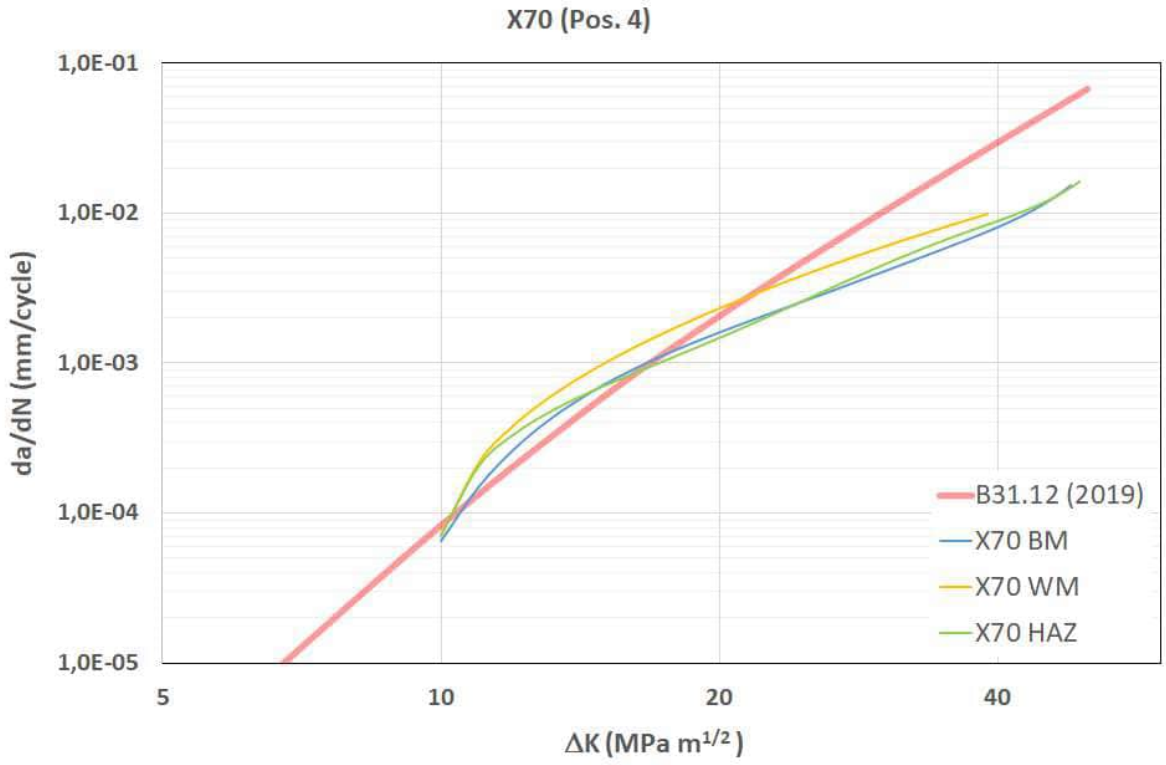


Figure 3.18: Crack growth X70 (item no. 4)

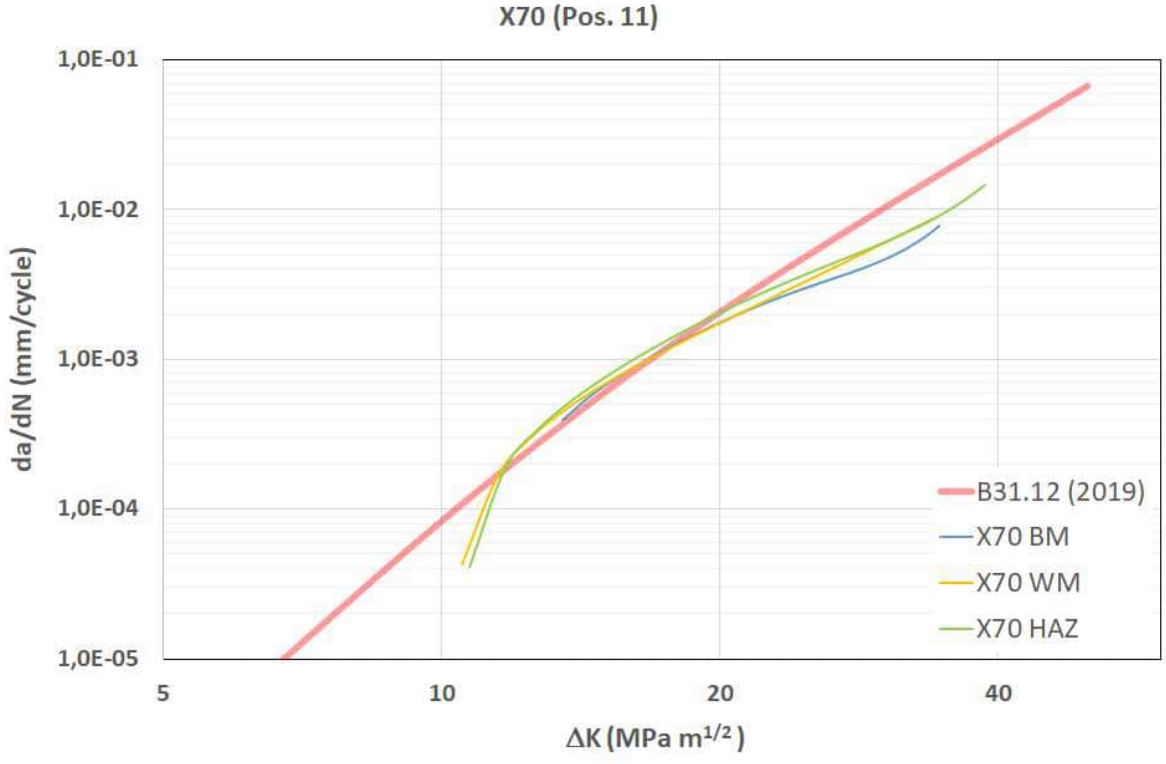


Figure 3.19: Crack growth X70 (item no. 11)

3.21 L485

The samples from items nos. 17, 32, 33, 34, 35, 36, 37, 38, 40 and 43 were taken from a spiral welded pipe with a diameter of 1016 mm and a wall thickness of 16.8 mm. The samples from item no. 2 were taken from a spiral welded pipe with a diameter of 1200 mm and a wall thickness of 23 mm.

The relevant material-specific data for the first-mentioned item numbers is as follows:

Table 3.64: Characteristics of L485

Production year	2017	
Production standards	DIN EN ISO 3183 Annex M	
Specific minimum characteristics[16]	R_e [MPa]	485
	R_m [MPa]	605
	K_v [J]	90
Material characteristics	R_e [MPa]	527
	R_m [MPa]	627
	K_v[17] [J]	280

Table 3.65: Chemical composition of L485

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.05	0.229	1.41	0.01	0.001	0.181	0.034	0.004
	Ni	V	Ti	Nb				
	0.258	0.004	0.038	0.059				

[16] As per DIN EN ISO 3181 and RN 268-022 (May 2016)
[17] Notched-bar impact test as per Charpy (DIN EN ISO 148) with V-notch at 0 °C

Table 3.66: Fracture toughness of L485

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
L485	Base material	2	134.2
L485	Weld material	2	129.8
L485	Heat-affected zone	2	92.4
L485	Base material	17	124.3
L485	Weld material	17	146.5
L485	Weld material of girth weld	17	100.8
L485	Base material (air)	32	480.4[18]
L485	Base material (0.2 bar)	33	203.2
L485	Base material (1 bar)	34	198.6
L485	Base material (2 bar)	35	186.7
L485	Base material (5 bar)	36	173.9
L485	Base material (10 bar)	37	175.8
L485	Base material (20 bar)	38	163.6
L485	Weld material of girth weld (hardened)	40	74.4 (crack)
L485	Heat-affected zone of girth weld (hardened)	40	67.9
L485	Weld material of heat-affected zone	43	148.8
L485	Weld material of girth weld	43	100.8

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- heat-affected zone of the girth weld
- heat-affected zone

[18] Estimated value since, due to the toughness properties of the material, evaluation could not be performed as per standard practice

Furthermore, crack growth was also established at an R value of 0.1 and 0.7. These curves are shown below.

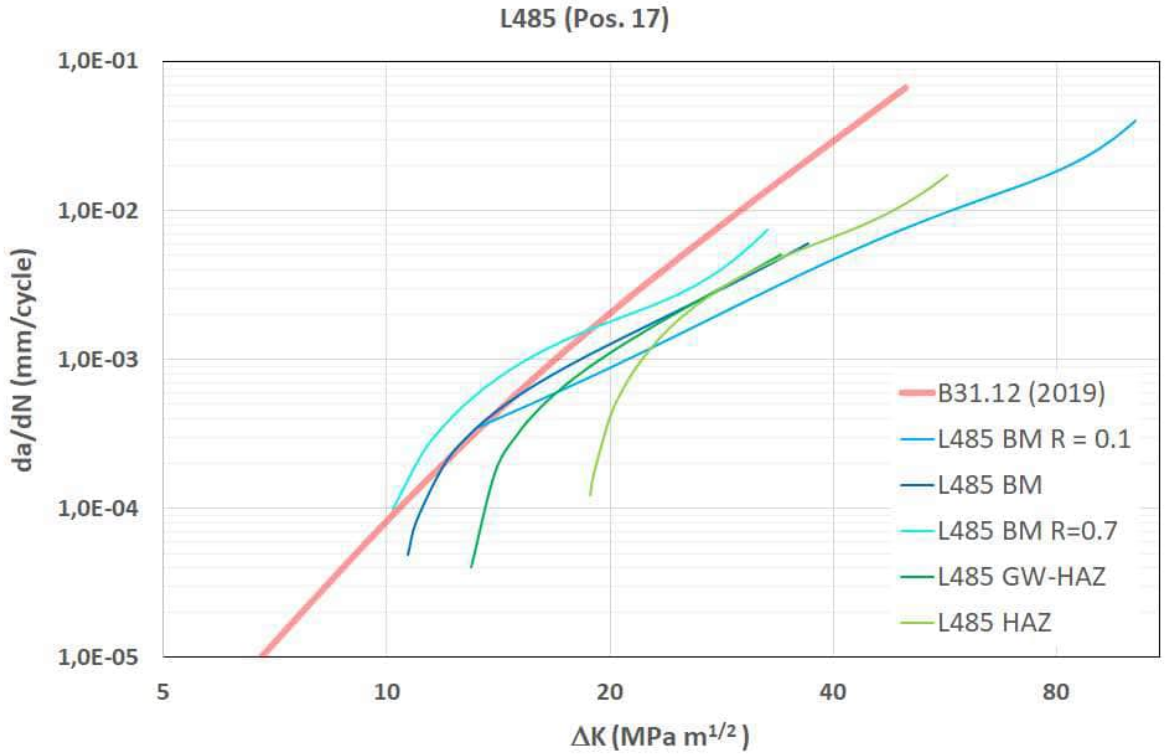


Figure 3.82: Crack growth L485 (item no. 17)

Furthermore, this material was investigated at different hydrogen pressures of 0 bar, 0.2 bar, 1 bar, 2 bar, 5 bar, 10 bar and 20 bar. The curves are shown below.

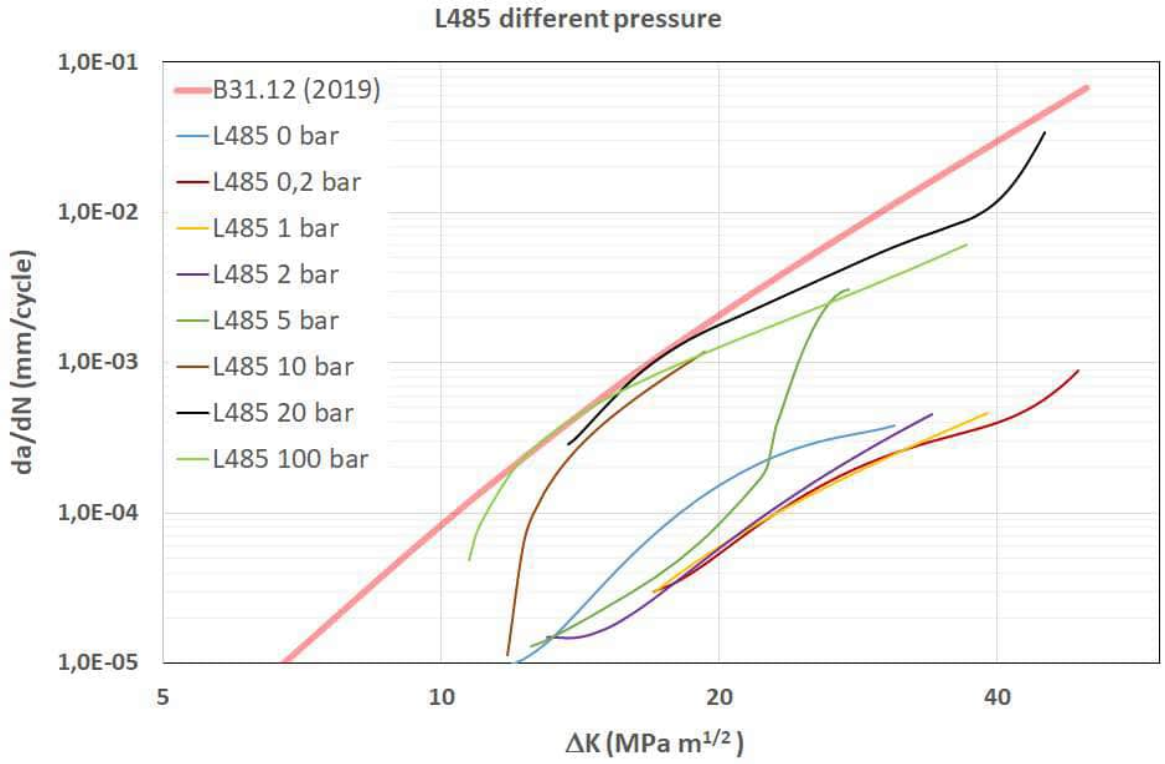


Figure 3.83: Crack growth L485 at different pressures

The curves describing crack growth at item no. 43 (girth weld area tempered to Ø 296 HV) in hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- weld material
- heat-affected zone

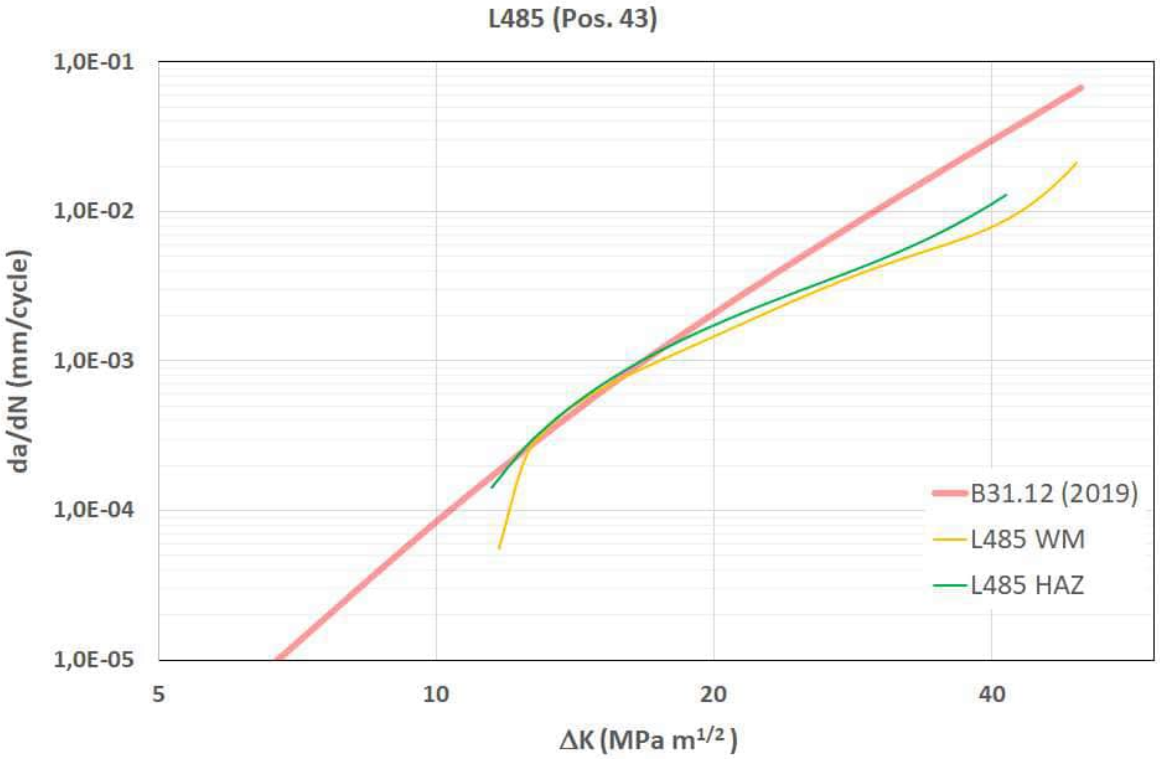


Figure 3.84: Crack growth L485 (item no. 43; tempered)

In order to achieve maximum hardness, the samples from item no. 40 were quenched in water. The hardness of these samples (from the area of the girth weld near the inner surface) was approx. 360 HV.

Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Graphical test evaluation (item no. 40) shows that considerable crack acceleration (instable crack growth) occurred even at relatively low cyclical stress intensities.

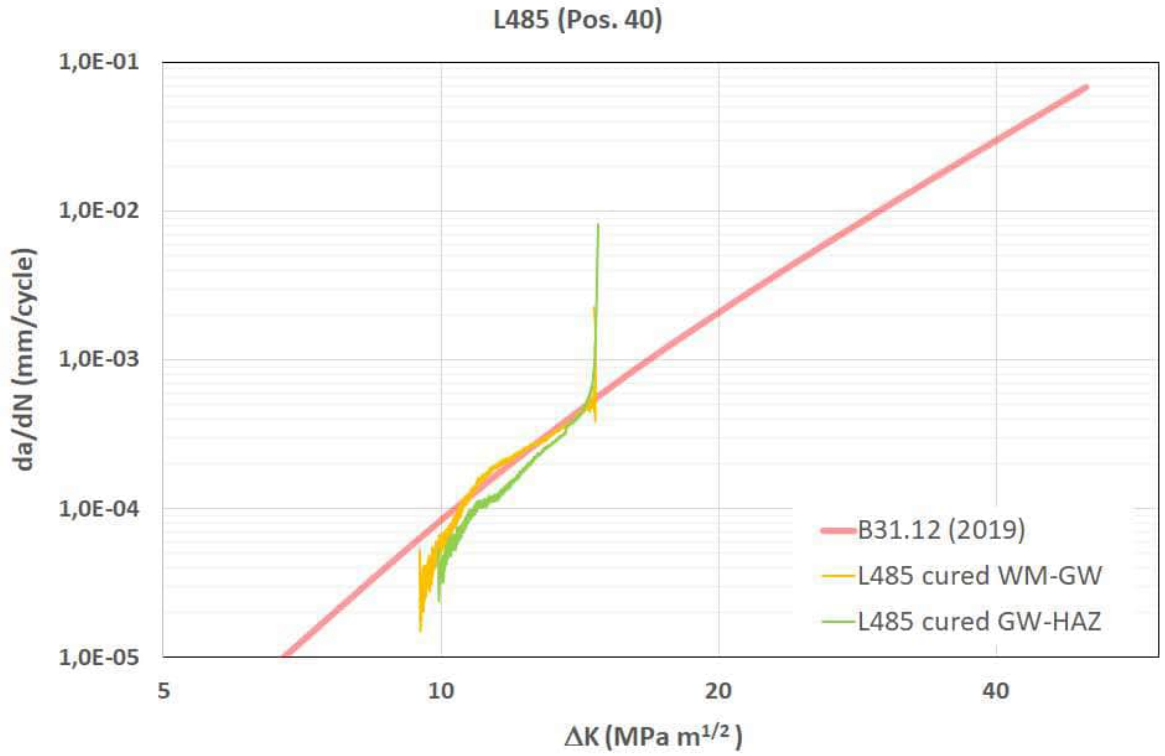


Figure 3.85: Crack growth L485 (hardened)

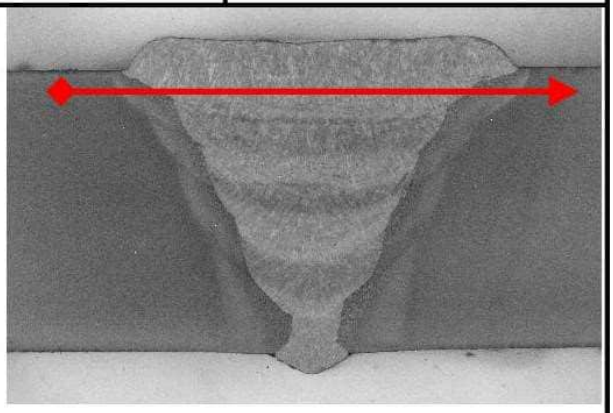
Hardness measurements were performed on two metallographic samples from item no. 17 and on one metallographic sample from item no. 40. The results of the hardness measurements for item no. 17 are shown in Figures 3.86 to 3.89 and for item no. 40 in Figures 3.90 to 3.91.

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	17.1; **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	287,1	289,1	0,2881	223	227		BM 1
2	283,1	288,9	0,2860	227			
3	285,2	287,1	0,2861	227			
4	282,7	286,0	0,2844	229			
5	282,9	287,7	0,2853	228			
1	290,4	290,6	0,2905	220	220		HAZ 1
2	288,5	291,4	0,2900	221			
3	290,6	293,3	0,2919	218			
4	291,4	290,4	0,2909	219			
5	284,4	291,2	0,2878	224			
1	285,8	279,8	0,2828	232	228		WM
2	283,1	285,6	0,2844	229			
3	285,2	284,8	0,2850	228			
4	288,9	286,0	0,2875	224			
5	284,8	287,7	0,2862	226			
1	286,6	286,4	0,2865	226	228		HAZ 2
2	284,4	289,5	0,2870	225			
3	280,2	284,8	0,2825	232			
4	285,2	282,3	0,2837	230			
5	283,8	288,3	0,2860	227			
1	288,1	291,4	0,2898	221	227		BM 2
2	287,7	288,9	0,2883	223			
3	283,3	288,7	0,2860	227			
4	283,1	286,2	0,2847	229			
5	280,4	283,3	0,2819	233			

Date: 06.11.22

Tester: Scheck

Figure 3.86: Hardness measurements of L485, item no. 17 (1)

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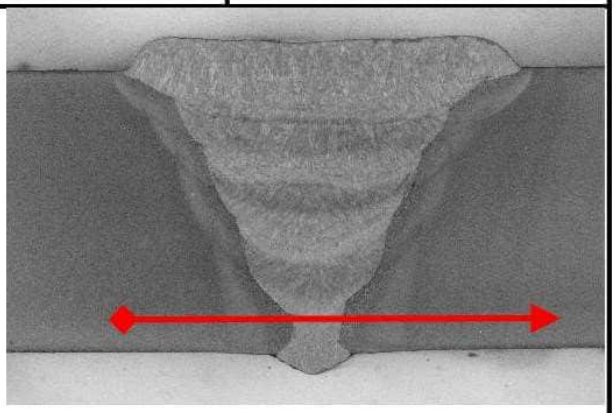
Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	17.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	285,2	293,1	0,2891	222	220		BM 1
2	287,1	291,0	0,2890	222			
3	287,1	292,7	0,2899	221			
4	289,3	294,3	0,2918	218			
5	290,6	294,1	0,2923	217			
1	286,0	288,3	0,2872	225	231		HAZ 1
2	282,3	282,3	0,2823	233			
3	280,6	282,1	0,2814	234			
4	280,2	278,3	0,2793	238			
5	286,0	285,8	0,2859	227			
1	284,2	285,8	0,2850	228	229		WM
2	278,8	280,4	0,2796	237			
3	281,2	283,5	0,2824	233			
4	287,7	287,7	0,2877	224			
5	286,4	290,0	0,2882	223			
1	296,8	293,3	0,2950	213	230		HAZ 2
2	287,7	284,4	0,2860	227			
3	285,0	286,4	0,2857	227			
4	279,8	275,0	0,2774	241			
5	274,8	278,1	0,2765	243			
1	286,4	285,8	0,2861	227	229		BM 2
2	285,0	289,3	0,2872	225			
3	280,0	286,2	0,2831	231			
4	283,7	287,9	0,2858	227			
5	277,9	284,8	0,2813	234			

Date: 06.11.22

Tester: Scheck

Figure 3.87: Hardness measurements of L485, item no. 17 (2)

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Test report
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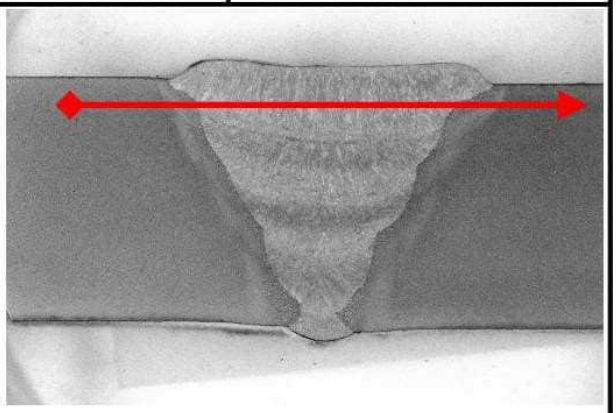
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	17.2; **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	284,4	293,9	0,2891	222	223		BM 1
2	285,2	290,2	0,2877	224			
3	286,0	286,9	0,2864	226			
4	286,2	289,8	0,2880	224			
5	289,1	291,8	0,2905	220			
1	292,0	291,0	0,2915	218	214		HAZ 1
2	293,3	288,5	0,2909	219			
3	294,1	291,0	0,2926	217			
4	296,4	293,3	0,2949	213			
5	302,8	299,7	0,3013	204			
1	282,9	286,6	0,2848	229	229		WM
2	285,4	282,1	0,2837	230			
3	287,1	284,6	0,2858	227			
4	285,6	281,7	0,2836	231			
5	285,4	285,6	0,2855	228			
1	294,6	290,4	0,2925	217	220		HAZ 2
2	288,3	282,7	0,2855	227			
3	281,7	282,3	0,2820	233			
4	288,5	292,4	0,2905	220			
5	301,0	301,4	0,3012	204			
1	289,8	289,8	0,2898	221	224		BM 2
2	285,6	288,1	0,2869	225			
3	286,7	289,5	0,2881	223			
4	283,7	287,1	0,2854	228			
5	285,8	290,4	0,2881	223			

Date: 06.11.22

Tester: Scheck

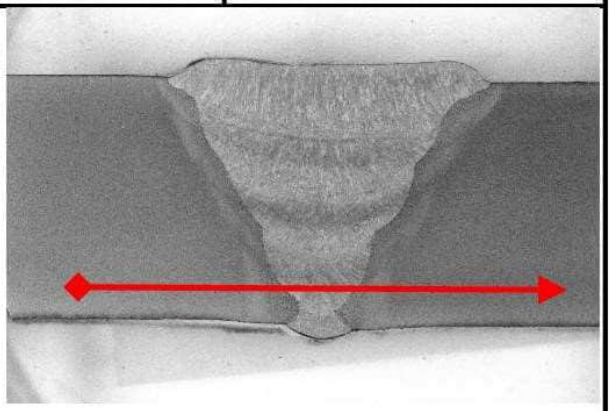
Figure 3.88: Hardness measurements of L485, item no. 17 (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	17.2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	287,1	292,5	0,2898	221	220		BM 1
2	287,7	290,4	0,2890	222			
3	288,7	293,3	0,2910	219			
4	289,8	293,9	0,2918	218			
5	286,9	292,7	0,2898	221			
1	308,0	309,3	0,3086	195	204		HAZ 1
2	301,0	308,2	0,3046	200			
3	295,4	299,1	0,2972	210			
4	300,8	299,9	0,3003	206			
5	295,4	296,4	0,2959	212			
1	314,7	293,5	0,3041	201	212		WM
2	292,9	295,6	0,2942	214			
3	292,5	290,6	0,2915	218			
4	293,9	296,0	0,2949	213			
5	296,2	295,4	0,2958	212			
1	307,4	305,5	0,3065	197	210		HAZ 2
2	298,1	302,8	0,3004	205			
3	296,6	298,1	0,2974	210			
4	290,4	292,1	0,2912	219			
5	292,7	290,4	0,2915	218			
1	285,4	288,9	0,2872	225	228		BM 2
2	282,7	286,7	0,2847	229			
3	285,6	290,8	0,2882	223			
4	282,3	285,4	0,2838	230			
5	281,0	285,8	0,2834	231			

Date: 06.11.22

Tester: Scheck

Figure 3.89: Hardness measurements of L485, item no. 17 (4)

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Test report
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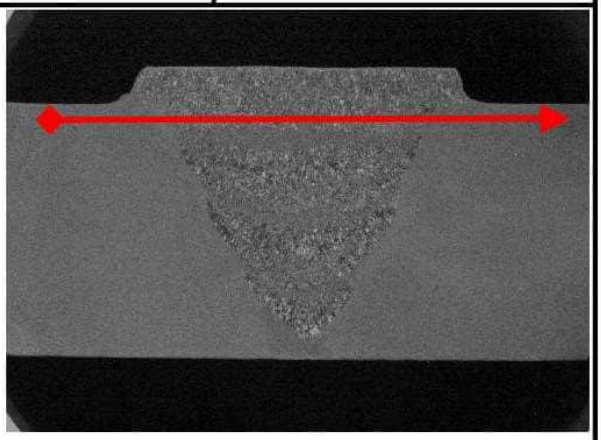
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	40.1; **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	232,5	231,6	0,2321	344	351		BM 1
2	230,0	230,2	0,2301	350			
3	229,6	230,2	0,2299	351			
4	228,5	228,5	0,2285	355			
5	229,2	228,7	0,2289	354			
1	233,7	233,3	0,2335	340	334		HAZ 1
2	237,4	235,4	0,2364	332			
3	235,8	238,9	0,2374	329			
4	235,8	238,1	0,2369	330			
5	233,9	233,5	0,2337	339			
1	234,1	226,0	0,2301	350	345		WM
2	232,9	232,9	0,2329	342			
3	230,2	232,9	0,2315	346			
4	235,0	228,7	0,2319	345			
5	231,9	233,3	0,2326	343			
1	230,0	229,4	0,2297	352	343		HAZ 2
2	232,9	232,1	0,2325	343			
3	234,1	231,0	0,2326	343			
4	233,1	233,3	0,2332	341			
5	232,9	235,4	0,2341	338			
1	230,8	228,9	0,2299	351	346		BM 2
2	230,8	232,3	0,2315	346			
3	230,6	231,4	0,2310	347			
4	231,6	231,0	0,2313	347			
5	233,3	233,5	0,2334	340			

Date: 06.11.22

Tester: Scheck

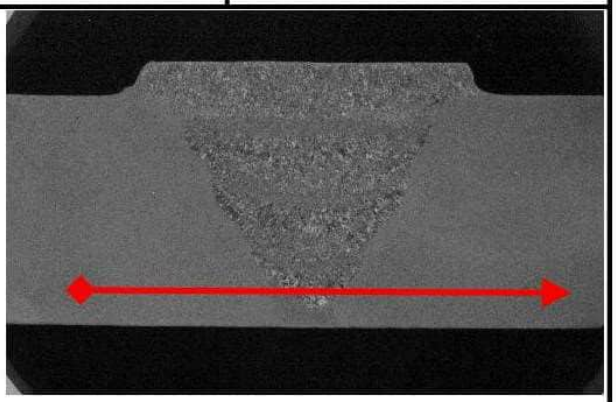
Figure 3.90: Hardness measurements of L485, item no. 40 (5)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	40.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	232,9	232,3	0,2326	343	350		BM 1
2	231,7	230,2	0,2309	348			
3	229,8	230,8	0,2303	350			
4	229,8	228,9	0,2294	352			
5	226,9	229,6	0,2282	356			
1	229,6	228,9	0,2293	353	365		HAZ 1
2	227,7	227,9	0,2278	357			
3	227,7	224,2	0,2259	363			
4	218,8	220,6	0,2197	384			
5	224,6	225,2	0,2249	367			
1	228,9	232,3	0,2306	349	366		WM
2	234,5	230,8	0,2327	343			
3	227,7	228,3	0,2280	357			
4	216,9	217,1	0,2170	394			
5	220,0	218,4	0,2192	386			
1	241,6	243,1	0,2423	316	345		HAZ 2
2	229,2	230,2	0,2297	352			
3	229,6	227,7	0,2286	355			
4	230,2	230,0	0,2301	350			
5	229,8	230,0	0,2299	351			
1	228,7	228,3	0,2285	355	350		BM 2
2	228,5	230,6	0,2296	352			
3	231,0	230,4	0,2307	348			
4	230,0	230,8	0,2304	349			
5	231,6	230,8	0,2312	347			

Date: 06.11.22

Tester: Scheck

Figure 3.91: Hardness measurements of L485, item no. 40 (6)

The samples from item no. 2 were taken from a spiral welded pipe with a diameter of 1200 mm and a wall thickness of 23 mm.

The relevant material-specific data is as follows:

Table 3.67: Characteristics of L485

Production year	2009	
Production standard	DIN EN ISO 3183 Annex M	
Specific minimum characteristics	R_e [MPa]	485
	R_m [MPa]	570
	K_v [J]	58
Material characteristics	R_e [MPa]	559
	R_m [MPa]	656
	K_v [J]	230

Table 3.68: Chemical composition of L485

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.096	0.313	1.729	0.013		0.145	0.016	
	Ni	V	Ti	Nb				
	0.202	0.008	0.027	0.045				

The results of crack growth investigations in hydrogen are as follows:

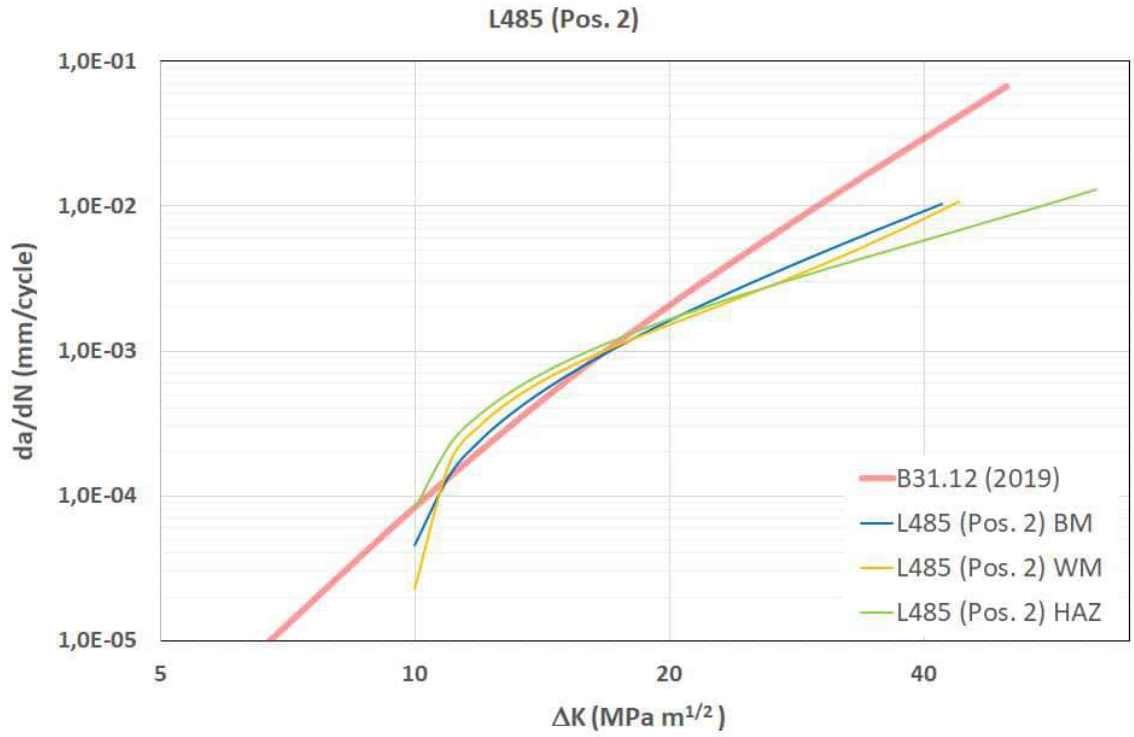


Figure 3.92: Crack growth in L485 (item no. 2)

Hardness measurements were performed on two metallographic samples from item no. 2. The results of these hardness measurements are shown in Figures 3.93 to 3.98.

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Test report
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Hardness test

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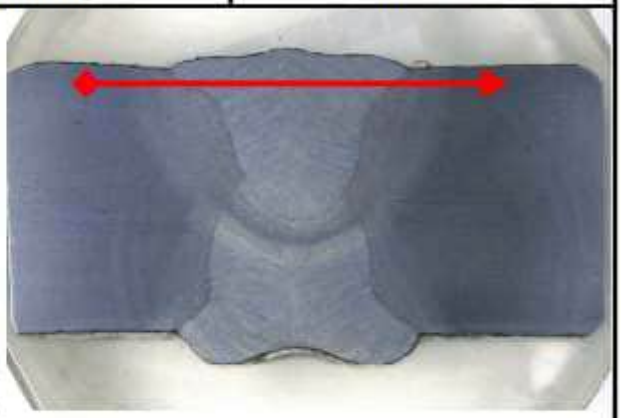
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	2.1 **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	285,0	283,1	0,2841	230	228		BM 1
2	282,1	285,8	0,2839	230			
3	281,2	287,1	0,2841	230			
4	282,5	289,5	0,2860	227			
5	280,0	295,4	0,2877	224			
1	312,6	306,4	0,3095	194	207		HAZ 1
2	299,9	299,9	0,2999	206			
3	297,2	297,6	0,2974	210			
4	295,6	298,3	0,2969	210			
5	293,7	297,2	0,2955	212			
1	293,1	298,1	0,2956	212	214		WM
2	292,9	297,9	0,2954	213			
3	292,0	293,9	0,2930	216			
4	292,7	294,1	0,2934	215			
5	295,4	292,9	0,2941	214			
1	303,2	304,9	0,3041	201	208		HAZ 2
2	302,6	297,8	0,3002	206			
3	297,9	294,9	0,2964	211			
4	302,6	292,7	0,2977	209			
5	298,7	294,7	0,2967	211			
1	275,2	287,3	0,2812	234	238		BM 2
2	273,4	283,9	0,2787	239			
3	273,4	286,9	0,2801	236			
4	271,5	283,8	0,2776	241			
5	272,3	284,8	0,2786	239			

Date: 06.11.22

Tester: Scheck

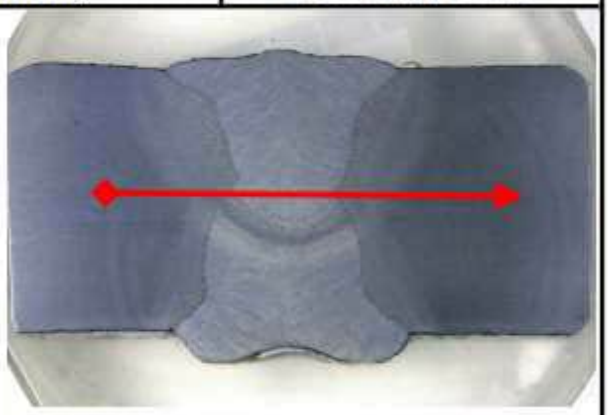
Figure 3.93: Hardness measurements of L485, item no. 2 (1)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und
Elektronenmikroskopie

Order number	9039784000
Sample description	2.1 **Center**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	287,7	286,4	0,2871	225	226		BM 1
2	287,5	289,5	0,2885	223			
3	283,9	290,0	0,2870	225			
4	279,8	289,6	0,2847	229			
5	281,3	288,5	0,2849	228			
1	294,3	293,1	0,2937	215	208		HAZ 1
2	297,9	297,0	0,2974	210			
3	295,1	295,8	0,2955	212			
4	302,4	302,2	0,3023	203			
5	305,3	302,2	0,3038	201			
1	299,9	301,4	0,3007	205	213		WM
2	290,8	293,1	0,2919	218			
3	294,3	292,7	0,2935	215			
4	295,8	292,7	0,2942	214			
5	291,6	295,6	0,2936	215			
1	295,8	294,5	0,2952	213	210		HAZ 2
2	298,7	295,6	0,2971	210			
3	299,3	294,1	0,2967	211			
4	293,7	294,1	0,2939	215			
5	302,4	303,5	0,3029	202			
1	282,9	293,9	0,2884	223	220		BM 2
2	288,1	297,0	0,2926	217			
3	285,8	297,2	0,2915	218			
4	285,0	294,5	0,2898	221			
5	283,1	294,7	0,2889	222			

Date: 06.11.22

Tester: Scheck

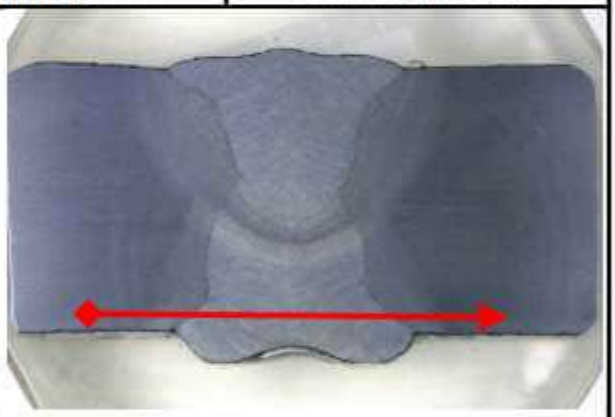
Figure 3.94: Hardness measurements of L485, item no. 2 (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	2.1 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	271,9	270,3	0,2711	252	247		BM 1
2	267,8	277,9	0,2728	249			
3	268,6	280,0	0,2743	246			
4	269,8	281,7	0,2757	244			
5	269,4	283,7	0,2766	242			
1	283,7	289,5	0,2866	226	219		HAZ 1
2	289,8	293,1	0,2914	218			
3	291,0	293,9	0,2925	217			
4	290,6	291,8	0,2912	219			
5	290,6	293,7	0,2922	217			
1	280,0	281,5	0,2807	235	228		WM
2	287,5	284,6	0,2860	227			
3	286,2	286,2	0,2862	226			
4	286,8	283,3	0,2851	228			
5	288,1	287,3	0,2877	224			
1	286,7	291,0	0,2888	222	217		HAZ 2
2	293,5	291,8	0,2927	217			
3	291,5	291,0	0,2913	219			
4	295,4	294,5	0,2950	213			
5	289,8	298,5	0,2941	214			
1	265,1	282,1	0,2736	248	255		BM 2
2	264,0	273,4	0,2687	257			
3	262,6	274,4	0,2685	257			
4	262,4	275,4	0,2689	256			
5	261,9	274,4	0,2682	258			

Date: 06.11.22

Tester: Scheck

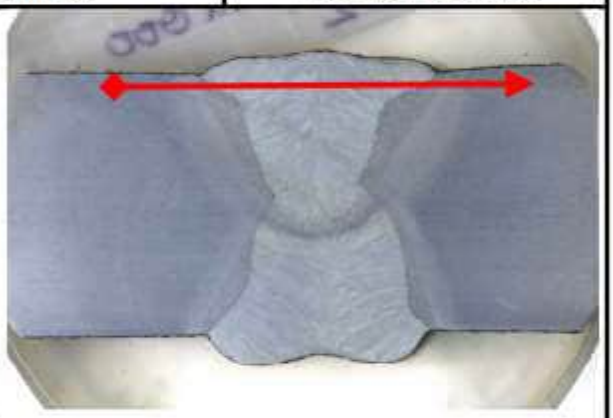
Figure 3.95: Hardness measurements of L485, item no. 2 (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	2.2 **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	268,4	277,1	0,2727	249	246		BM 1
2	265,7	280,0	0,2728	249			
3	268,4	280,8	0,2746	246			
4	269,0	282,3	0,2756	244			
5	270,0	285,4	0,2777	240			
1	294,0	292,0	0,2930	216	214		HAZ 1
2	294,1	297,8	0,2960	212			
3	288,9	298,5	0,2937	215			
4	298,5	294,7	0,2966	211			
5	291,8	290,8	0,2913	219			
1	291,0	291,4	0,2912	219	218		WM
2	293,7	294,5	0,2941	214			
3	289,5	290,2	0,2899	221			
4	291,4	291,4	0,2914	218			
5	292,5	291,2	0,2918	218			
1	317,6	314,7	0,3161	186	213		HAZ 2
2	289,6	288,1	0,2888	222			
3	290,0	297,0	0,2935	215			
4	286,2	290,0	0,2881	223			
5	295,2	288,5	0,2919	218			
1	279,4	291,6	0,2855	227	230		BM 2
2	278,8	289,3	0,2840	230			
3	276,1	288,3	0,2822	233			
4	277,7	288,3	0,2830	232			
5	282,3	290,6	0,2864	226			

Date: 06.11.22

Tester: Scheck

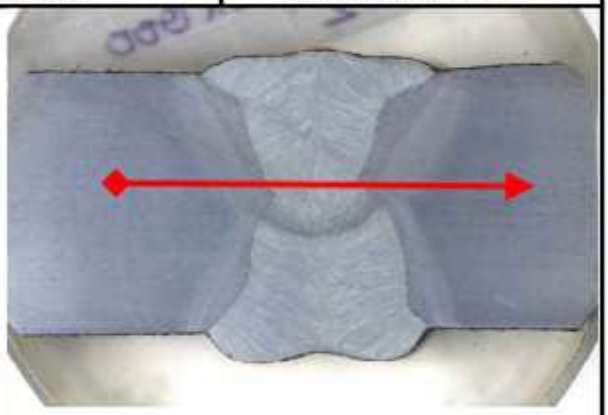
Figure 3.96: Hardness measurements of L485, item no. 2 (4)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	2.2 **Center**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	286,2	293,3	0,2898	221	226		BM 1
2	281,5	292,9	0,2872	225			
3	279,6	287,9	0,2837	230			
4	279,4	290,4	0,2849	228			
5	280,6	291,2	0,2859	227			
1	296,6	291,8	0,2942	214	211		HAZ 1
2	291,4	292,0	0,2917	218			
3	292,2	292,9	0,2926	217			
4	299,3	297,2	0,2983	208			
5	304,5	307,6	0,3060	198			
1	291,4	290,6	0,2910	219	215		WM
2	291,6	288,3	0,2900	221			
3	295,8	297,2	0,2965	211			
4	294,1	285,4	0,2898	221			
5	302,6	302,0	0,3023	203			
1	292,0	292,9	0,2925	217	214		HAZ 2
2	294,3	292,9	0,2936	215			
3	290,8	296,8	0,2938	215			
4	294,3	294,1	0,2942	214			
5	298,1	299,1	0,2986	208			
1	280,4	288,5	0,2845	229	230		BM 2
2	279,2	282,9	0,2810	235			
3	283,5	290,2	0,2868	225			
4	279,0	288,7	0,2838	230			
5	280,2	288,7	0,2845	229			

Date: 06.11.22

Tester: Scheck

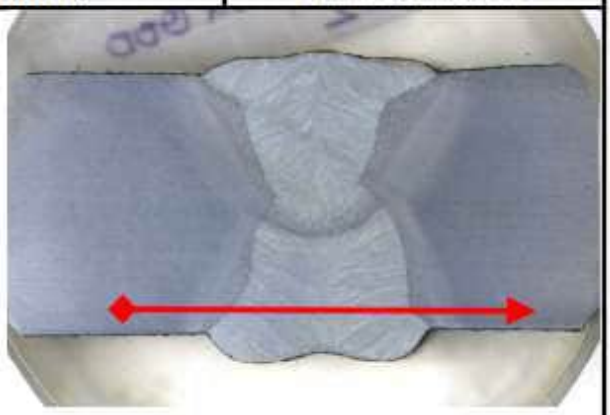
Figure 3.97: Hardness measurements of L485, item no. 2 (5)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	2.2 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	262,6	274,4	0,2685	257	256		BM 1
2	258,0	276,5	0,2672	260			
3	261,3	275,2	0,2683	258			
4	262,2	276,3	0,2692	256			
5	267,3	280,8	0,2741	247			
1	287,7	289,1	0,2884	223	216		HAZ 1
2	290,4	296,6	0,2935	215			
3	293,7	292,5	0,2931	216			
4	296,2	294,8	0,2955	212			
5	294,7	294,3	0,2945	214			
1	289,8	291,2	0,2905	220	222		WM
2	288,7	287,7	0,2882	223			
3	292,7	287,9	0,2903	220			
4	286,2	287,1	0,2866	226			
5	291,2	290,0	0,2906	220			
1	289,3	286,8	0,2881	223	222		HAZ 2
2	291,0	288,3	0,2896	221			
3	284,6	290,4	0,2875	224			
4	285,8	285,8	0,2858	227			
5	294,7	294,5	0,2946	214			
1	269,6	281,7	0,2756	244	248		BM 2
2	267,6	280,6	0,2741	247			
3	264,6	278,3	0,2715	252			
4	265,1	276,3	0,2707	253			
5	269,4	280,2	0,2748	246			

Date: 06.11.22

Tester: Scheck

Figure 3.98: Hardness measurements of L485, item no. 2 (6)

3.22 L485 ME

The samples were taken from a pipe with a diameter of 813 mm and a wall thickness of 17.5 mm.

The relevant material-specific data is as follows:

Table 3.69: Characteristics of L485 ME

Production year	2017	
Production standards	ISO 3183	
Specific minimum characteristics[19]	R_e [MPa]	485
	R_m [MPa]	570
	K_v [J]	48
Material characteristics	R_e [MPa]	520
	R_m [MPa]	621
	K_v[20] [J]	183

Table 3.70: Chemical composition of L485 ME

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.08	0.35	1.59	0.015	0.002	0.04	0.09	0.01
	Ni	V	Ti	Nb				
	0.06		0.01	0.04				

Table 3.71: Fracture toughness of L485 ME

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
L485 ME	Base material		115 (100 bar) / 154 (10 bar)
L485 ME	Weld material		159 (100 bar) / 179 (10 bar)

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar and 10 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material

[19] As per DIN EN ISO 3181 and RN 268-022 (May 2016)
[20] Notched-bar impact test as per Charpy (DIN EN ISO 148) with V-notch at 0 °C

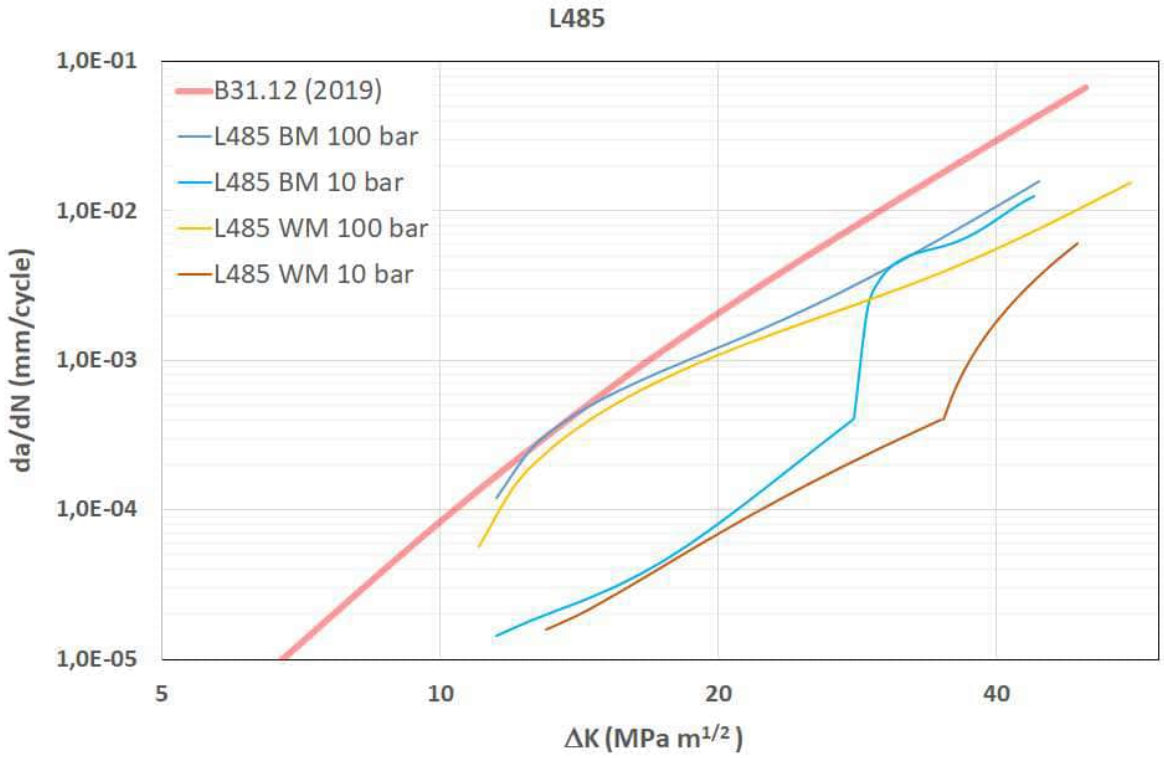


Figure 3.99: Crack growth L485

3.23 L485 (Batch 2)

The samples were taken from a longitudinally welded pipe.

The relevant material-specific data is as follows:

Table 3.72: Characteristics of L485 (batch 2)

Production year	2022	
Production standards	DIN EN ISO 3183, Annex M	
Specific minimum characteristics	R_e [MPa]	485
	R_m [MPa]	605
	K_v [J]	90
Material characteristics	R_e [MPa]	521
	R_m [MPa]	632
	K_v [21][J]	264

Table 3.73: Chemical composition of L485 (batch 2)

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.084	0.35	1.75	0.014	0.0007	0.03	0.04	0.01
	Ni	V	Ti	Nb				
	0.04		0.014	0.045				

Table 3.74: Fracture toughness of L485 (batch 2)

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
L485	Base material	47	106.3
L485	Weld material	47	163.6

The curves describing crack growth in fatigue testing in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material

[21] Notched-bar impact test as per Charpy (DIN EN ISO 148) with V-notch at 20 °C

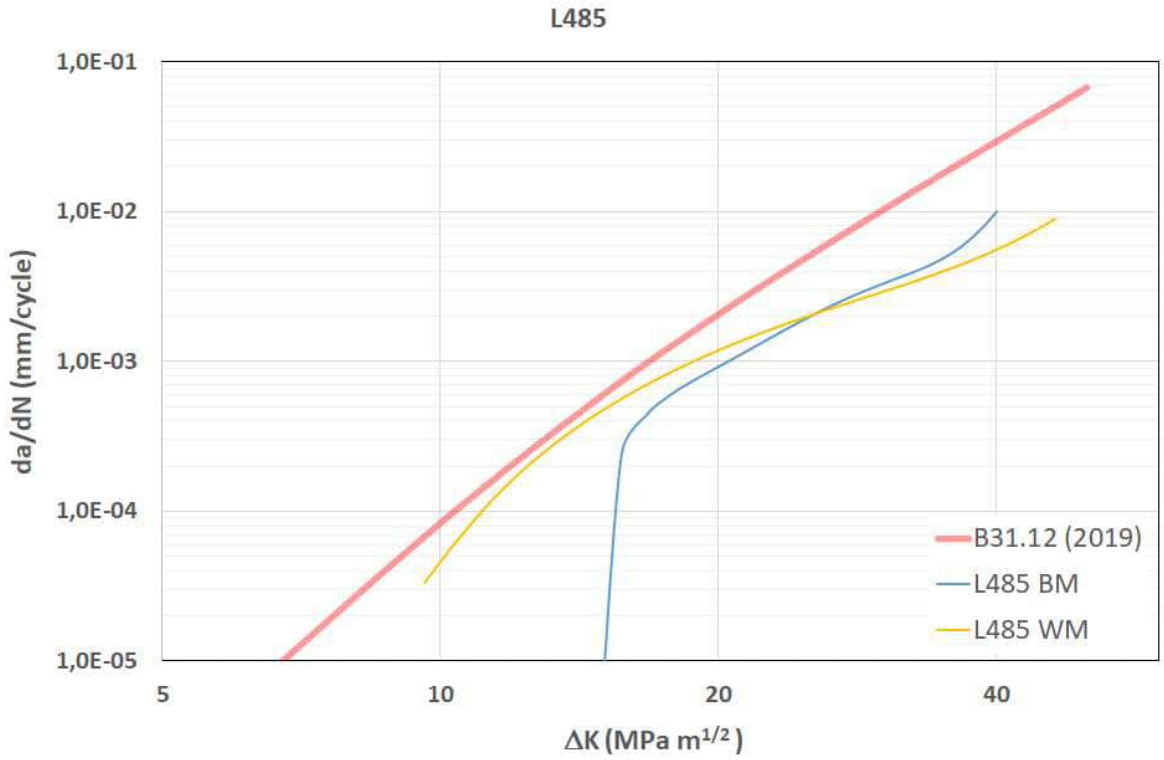


Figure 3.100: Crack growth L485 (batch 2)

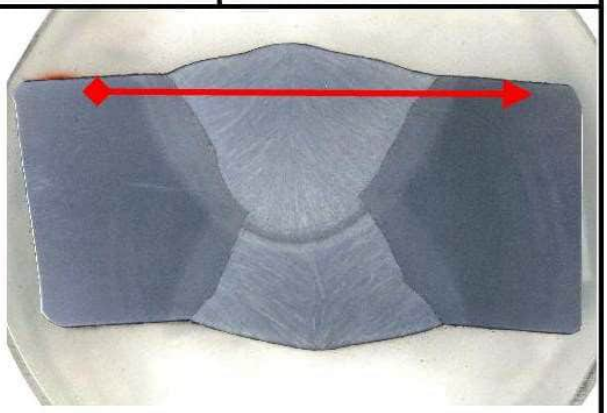
Hardness measurements were performed on two metallographic samples from item no. 47. The results of these hardness measurements are shown in Figures 3.101 to 3.106.

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	47.1 **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	313,8	327,1	0,3205	181	186		BM 1
2	313,6	327,3	0,3205	181			
3	309,3	320,3	0,3148	187			
4	297,6	314,0	0,3058	198			
5	308,0	325,5	0,3167	185			
1	308,6	311,5	0,3101	193	206		HAZ 1
2	289,3	296,6	0,2930	216			
3	294,5	295,4	0,2949	213			
4	298,1	298,9	0,2985	208			
5	303,5	302,2	0,3028	202			
1	286,9	291,0	0,2889	222	218		WM
2	291,2	289,8	0,2905	220			
3	294,3	290,8	0,2926	217			
4	294,5	292,9	0,2937	215			
5	293,5	289,3	0,2914	218			
1	295,3	294,2	0,2948	213	211		HAZ 2
2	299,5	296,8	0,2982	209			
3	297,4	301,4	0,2994	207			
4	294,9	294,1	0,2945	214			
5	294,8	294,3	0,2945	214			
1	315,5	330,9	0,3232	178	181		BM 2
2	314,3	326,7	0,3205	181			
3	311,6	326,3	0,3189	182			
4	312,6	324,0	0,3183	183			
5	315,1	329,0	0,3220	179			

Date: 06.11.22

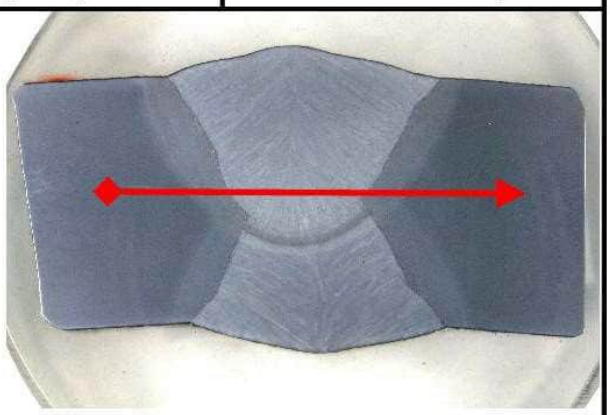
Tester: Scheck

Figure 3.101: Hardness measurements of L485, item no. 47 (1)

MPA STUTTGART	**Test report** MPAS-PPB 52310-08/1 Hardness test	**Referat** Metallographie und Elektronenmikroskopie

Order number 9039784000
Sample description 47.1 Center
Administrator Silcher
Test instrument Zwick Z 323 (neu)
Serial number H2932-002-50430
Test conditions

☑ HV **10** DIN EN ISO 6507-1:2018-07
☐ HBW DIN EN ISO 6506-1:2015-02
☐ HRC DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	306,2	319,2	0,3127	190	185		BM 1
2	312,6	324,0	0,3183	183			
3	310,7	320,7	0,3157	186			
4	310,3	323,2	0,3167	185			
5	312,8	324,2	0,3185	183			
1	302,8	298,9	0,3009	205	210		HAZ 1
2	297,9	297,6	0,2978	209			
3	295,8	296,8	0,2963	211			
4	298,5	297,4	0,2980	209			
5	295,2	290,6	0,2929	216			
1	290,4	290,6	0,2905	220	220		WM
2	290,6	291,8	0,2912	219			
3	290,4	292,0	0,2912	219			
4	289,3	286,0	0,2877	224			
5	290,6	289,5	0,2901	220			
1	298,3	302,2	0,3002	206	209		HAZ 2
2	298,9	299,3	0,2991	207			
3	294,5	297,0	0,2958	212			
4	294,7	297,6	0,2962	211			
5	296,6	299,3	0,2980	209			
1	311,8	324,6	0,3182	183	188		BM 2
2	306,8	320,5	0,3136	189			
3	307,6	318,2	0,3129	189			
4	308,0	318,8	0,3134	189			
5	306,4	317,6	0,3120	191			

Date: 06.11.22
Tester: Scheck

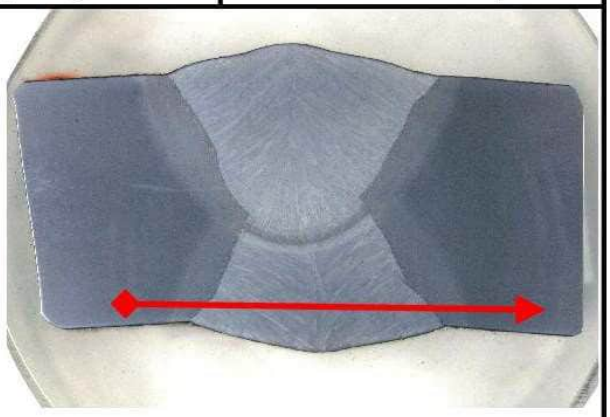
Figure 3.102: Hardness measurements of L485, item no. 47 (2)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	47.1 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	311,3	318,8	0,3151	187	189		BM 1
2	307,2	318,2	0,3127	190			
3	308,4	316,7	0,3126	190			
4	305,9	318,0	0,3120	191			
5	307,0	318,0	0,3125	190			
1	295,6	292,2	0,2939	215	208		HAZ 1
2	301,4	306,0	0,3037	201			
3	298,5	301,6	0,3000	206			
4	293,3	299,5	0,2964	211			
5	299,9	302,4	0,3012	204			
1	291,8	294,1	0,2930	216	217		WM
2	295,2	291,8	0,2935	215			
3	292,2	290,4	0,2913	219			
4	290,4	292,0	0,2912	219			
5	290,8	292,0	0,2914	218			
1	295,6	298,9	0,2972	210	206		HAZ 2
2	299,1	303,2	0,3012	204			
3	299,9	300,8	0,3003	206			
4	302,8	300,1	0,3015	204			
5	297,7	303,7	0,3007	205			
1	313,6	324,6	0,3191	182	182		BM 2
2	310,9	324,8	0,3179	184			
3	313,4	324,4	0,3189	182			
4	313,4	324,8	0,3191	182			
5	313,4	326,3	0,3198	181			

Date: 06.11.22

Tester: Scheck

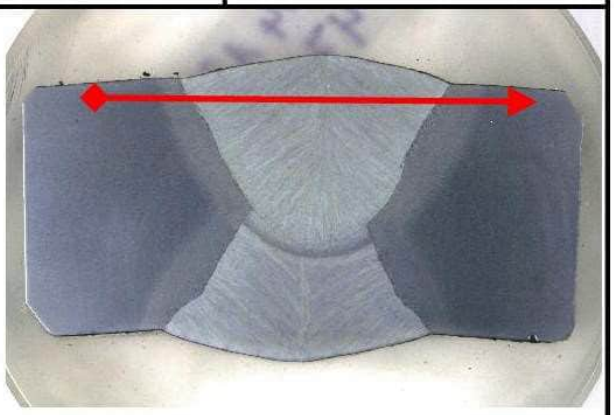
Figure 3.103: Hardness measurements of L485, item no. 47 (3)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	47.2 **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	307,8	315,3	0,3116	191	187		BM 1
2	308,2	316,3	0,3123	190			
3	308,6	318,6	0,3136	189			
4	312,0	319,9	0,3159	186			
5	314,9	325,3	0,3201	181			
1	548,9	311,9	0,4304	100	188		HAZ 1
2	293,5	297,3	0,2954	213			
3	302,8	303,9	0,3034	202			
4	294,1	299,7	0,2969	210			
5	294,1	294,3	0,2942	214			
1	290,6	291,8	0,2912	219	219		WM
2	291,8	291,8	0,2918	218			
3	289,8	286,6	0,2882	223			
4	290,2	292,9	0,2915	218			
5	291,6	291,8	0,2917	218			
1	302,0	307,5	0,3047	200	206		HAZ 2
2	298,3	304,1	0,3012	204			
3	295,4	299,7	0,2975	209			
4	296,2	298,9	0,2975	209			
5	297,6	298,3	0,2980	209			
1	316,9	322,6	0,3198	181	186		BM 2
2	313,6	324,0	0,3188	182			
3	309,3	318,6	0,3139	188			
4	308,4	316,3	0,3124	190			
5	308,9	319,0	0,3139	188			

Date: 06.11.22

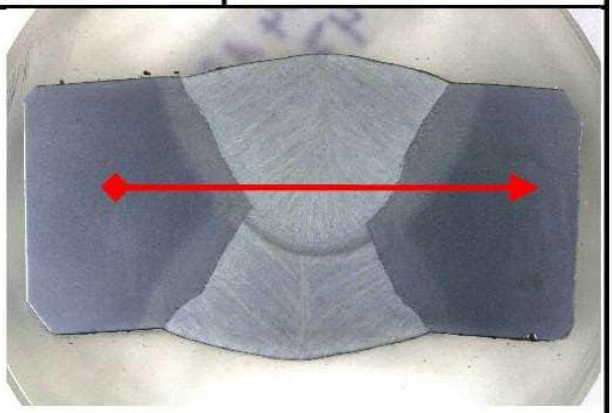
Tester: Scheck

Figure 3.104: Hardness measurements of L485, item no. 47 (4)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie



Order number	9039784000
Sample description	47.2 Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV 10	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	297,0	296,4	0,2967	211	195		BM 1
2	304,1	315,9	0,3100	193			
3	302,0	317,2	0,3096	193			
4	308,0	318,6	0,3133	189			
5	308,8	319,0	0,3139	188			
1	308,9	323,8	0,3163	185	204		HAZ 1
2	297,2	293,9	0,2956	212			
3	295,8	296,2	0,2960	212			
4	297,4	297,0	0,2972	210			
5	305,5	304,3	0,3049	199			
1	291,4	287,7	0,2896	221	218		WM
2	288,7	284,6	0,2866	226			
3	295,6	293,3	0,2944	214			
4	293,5	296,0	0,2947	213			
5	293,9	290,4	0,2921	217			
1	298,7	297,4	0,2981	209	210		HAZ 2
2	298,1	301,0	0,2995	207			
3	295,4	297,8	0,2966	211			
4	304,7	303,0	0,3039	201			
5	290,0	290,2	0,2901	220			
1	315,5	326,3	0,3209	180	189		BM 2
2	312,8	320,1	0,3164	185			
3	309,7	315,9	0,3128	190			
4	311,1	310,7	0,3109	192			
5	309,9	305,0	0,3075	196			

Date: 06.11.22

Tester: Scheck

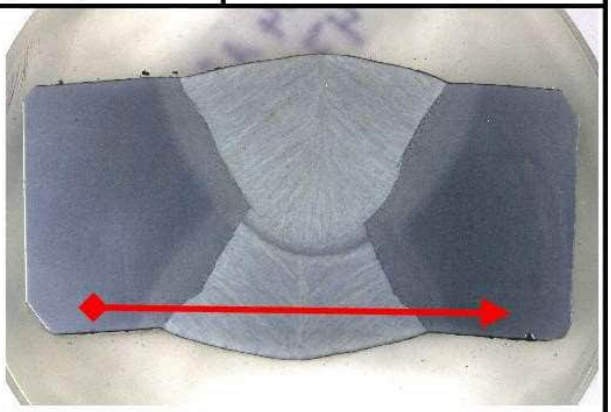
Figure 3.105: Hardness measurements of L485, item no. 47 (5)

MPA STUTTGART

Test report
MPAS-PPB 52310-08/1
Hardness test

Referat
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	47.2 **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	312,2	320,5	0,3163	185	187		BM 1
2	309,7	320,7	0,3152	187			
3	309,1	320,9	0,3150	187			
4	307,6	320,3	0,3139	188			
5	308,2	318,4	0,3133	189			
1	296,2	301,4	0,2988	208	204		HAZ 1
2	299,1	303,5	0,3013	204			
3	301,0	302,0	0,3015	204			
4	303,3	304,9	0,3041	201			
5	299,9	300,3	0,3001	206			
1	292,9	291,6	0,2923	217	217		WM
2	290,4	292,2	0,2913	219			
3	291,6	292,5	0,2920	217			
4	292,9	291,2	0,2920	217			
5	293,1	294,5	0,2938	215			
1	302,8	299,7	0,3013	204	206		HAZ 2
2	297,4	298,9	0,2982	209			
3	300,1	300,1	0,3001	206			
4	298,7	300,5	0,2996	207			
5	299,1	301,6	0,3003	206			
1	304,9	313,8	0,3094	194	190		BM 2
2	308,0	315,1	0,3116	191			
3	307,0	321,7	0,3144	188			
4	310,1	318,6	0,3144	188			
5	308,4	317,8	0,3131	189			

Date: 06.11.22

Tester: Scheck

Figure 3.106: Hardness measurements of L485, item no. 47 (6)

3.24 GRS550/X80

The samples were taken from a longitudinally welded pipe with a diameter of 1200 mm and a wall thickness of 18.3 mm.

The relevant material-specific data is as follows:

Table 3.75: Characteristics of GRS550/X80

Production year	1992	
Production standard	DIN 17172 / API STD 5L	
Specific minimum characteristics	R_e [MPa]	550
	R_m [MPa]	620
	K_v [J]	27
Material characteristics	R_e [MPa]	584
	R_m [MPa]	728
	K_v [22] [J]	130

Table 3.76: Chemical composition of GRS550/X80

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.1	0.4	1.97	0.016	0.001	0.03	0.05	0.01
	Ni	V	Ti	Nb				
	0.03		0.017	0.044				

Table 3.77: Fracture toughness of GRS550/X80

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
GRS550/X80	Base material	5	140.9
GRS550/X80	Weld material	5	154.2

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material of longitudinal weld

[22] Notched-bar impact test with V-notch at 0 °C

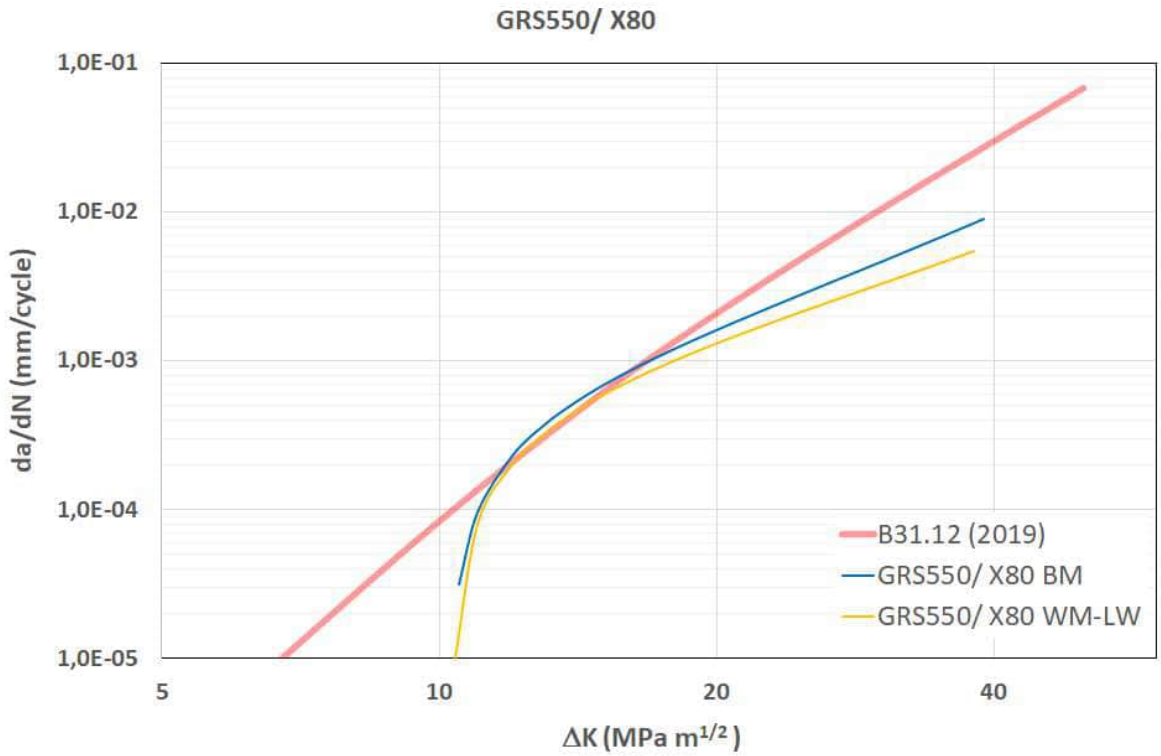


Figure 3.107: Crack growth GRS550/X80

Hardness measurements were performed on two metallographic samples from item no. 5. The results of these hardness measurements are shown in Figures 3.108 to 3.113.

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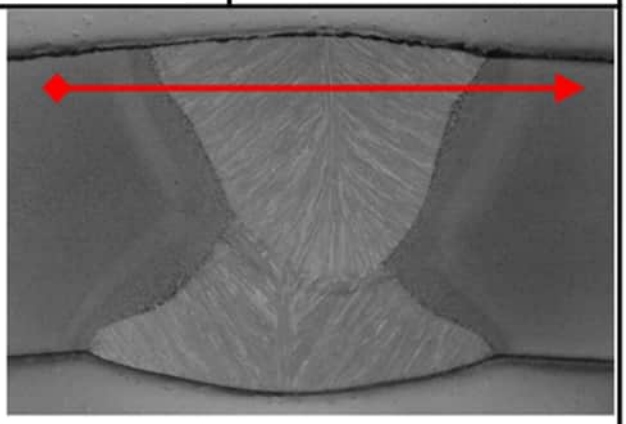
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	5.1; **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	292,0	300,6	0,2963	211	213		BM 1
2	289,3	302,8	0,2961	212			
3	283,9	296,2	0,2901	220			
4	290,6	299,7	0,2952	213			
5	293,9	304,7	0,2993	207			
1	295,0	294,0	0,2945	214	217		HAZ 1
2	290,2	294,7	0,2925	217			
3	293,1	291,2	0,2921	217			
4	286,4	295,6	0,2910	219			
5	289,5	294,9	0,2922	217			
1	280,0	277,7	0,2789	238	238		WM
2	281,7	283,7	0,2827	232			
3	279,6	277,5	0,2785	239			
4	274,4	273,8	0,2741	247			
5	283,3	281,5	0,2824	233			
1	286,6	293,5	0,2901	220	220		HAZ 2
2	286,0	292,5	0,2893	222			
3	292,1	288,9	0,2905	220			
4	292,5	288,3	0,2904	220			
5	289,1	294,3	0,2917	218			
1	296,6	306,8	0,3017	204	207		BM 2
2	298,5	306,2	0,3023	203			
3	290,4	303,2	0,2968	210			
4	292,9	303,7	0,2983	208			
5	293,3	303,0	0,2982	209			

Date: 06.11.22

Tester: Scheck

Figure 3.108: Hardness measurements of GRS550/X80 (1)

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Hardness test

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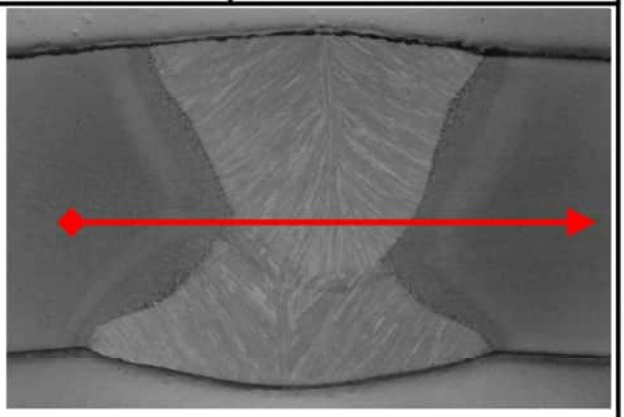

Order number	9039784000
Sample description	5.1; **Center**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐	Test temperatur, if outside (23+/-5) °C

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	**d_1 µm**	**d_2 µm**	**d_m mm**	**Hardness HV**	**Mean value HV**	**Distance in mm**	**Remark**
1	285,6	297,2	0,2914	218	214		BM 1
2	287,3	296,0	0,2916	218			
3	290,0	300,8	0,2954	213			
4	289,1	297,9	0,2935	215			
5	298,1	305,1	0,3016	204			
1	294,1	290,8	0,2925	217	217		HAZ 1
2	290,8	292,2	0,2915	218			
3	291,6	292,2	0,2919	218			
4	293,3	291,8	0,2926	217			
5	293,1	291,2	0,2921	217			
1	281,0	281,0	0,2810	235	232		WM
2	284,6	282,7	0,2836	230			
3	284,6	284,4	0,2845	229			
4	282,3	279,4	0,2808	235			
5	284,6	282,3	0,2834	231			
1	295,2	292,5	0,2938	215	218		HAZ 2
2	297,0	289,2	0,2931	216			
3	288,3	296,2	0,2923	217			
4	290,8	288,5	0,2897	221			
5	290,4	289,1	0,2898	221			
1	301,8	308,8	0,3053	199	209		BM 2
2	295,8	305,7	0,3008	205			
3	294,5	304,1	0,2993	207			
4	290,0	298,5	0,2942	214			
5	286,8	295,8	0,2913	219			

Date: 06.11.22

Tester: Scheck

Figure 3.109: Hardness measurements of GRS550/X80 (2)

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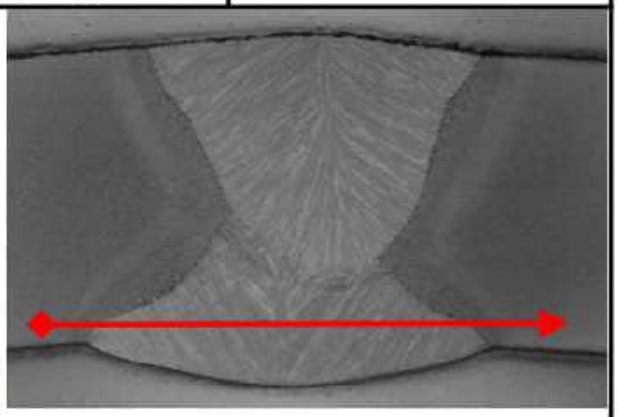
Order number	9039784000
Sample description	5.1; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	**235 HV**	Reference:	**237 HV 10**

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	292,2	300,1	0,2962	211	211		BM 1
2	291,6	300,1	0,2959	212			
3	292,7	299,7	0,2962	211			
4	292,3	298,7	0,2955	212			
5	294,5	299,3	0,2969	210			
1	279,8	284,0	0,2819	233	222		HAZ 1
2	291,8	290,4	0,2911	219			
3	295,0	289,8	0,2924	217			
4	296,2	289,6	0,2929	216			
5	288,5	283,3	0,2859	227			
1	285,2	277,3	0,2813	234	243		WM
2	278,4	278,1	0,2783	240			
3	278,8	276,9	0,2778	240			
4	272,5	268,8	0,2707	253			
5	275,2	270,7	0,2729	249			
1	276,7	270,9	0,2738	247	235		HAZ 2
2	274,8	275,2	0,2750	245			
3	278,5	284,8	0,2817	234			
4	286,2	288,7	0,2875	224			
5	286,0	286,2	0,2861	227			
1	297,2	302,4	0,2998	206	210		BM 2
2	295,2	302,6	0,2989	208			
3	288,7	302,6	0,2957	212			
4	291,0	300,1	0,2956	212			
5	288,9	299,7	0,2943	214			

Date: 06.11.22

Tester: Scheck

Figure 3.110: Hardness measurements of GRS550/X80 (3)

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Test report
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Hardness test

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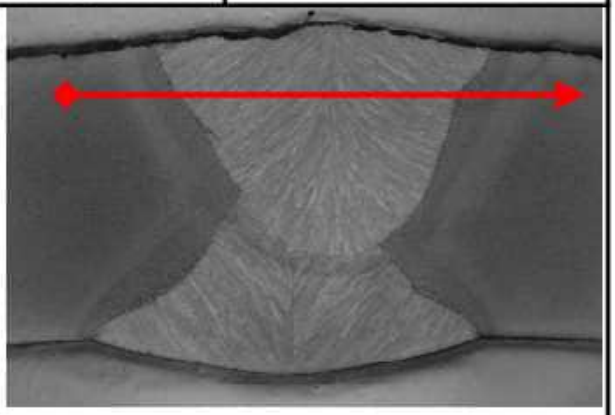

Order number	9039784000
Sample description	5.2; **Outer layer**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	291,2	305,4	0,2983	208	207		BM 1
2	294,3	304,7	0,2995	207			
3	292,2	304,3	0,2983	208			
4	292,0	303,5	0,2978	209			
5	297,6	306,2	0,3019	203			
1	296,8	298,9	0,2979	209	216		HAZ 1
2	297,7	289,8	0,2937	215			
3	289,0	294,8	0,2919	218			
4	290,0	290,8	0,2904	220			
5	290,2	292,0	0,2911	219			
1	280,6	282,7	0,2817	234	234		WM
2	283,5	282,9	0,2832	231			
3	283,9	281,3	0,2826	232			
4	282,1	276,5	0,2793	238			
5	281,7	281,9	0,2818	234			
1	296,0	291,6	0,2938	215	219		HAZ 2
2	291,6	293,7	0,2927	217			
3	288,5	292,2	0,2904	220			
4	293,7	287,5	0,2906	220			
5	280,4	292,9	0,2867	226			
1	299,7	305,5	0,3026	202	207		BM 2
2	297,2	308,5	0,3029	202			
3	292,9	302,8	0,2978	209			
4	292,9	302,4	0,2976	209			
5	289,6	299,3	0,2944	214			

Date: 06.11.22

Tester: Scheck

Figure 3.111: Hardness measurements of GRS550/X80 (4)

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Test report
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Hardness test

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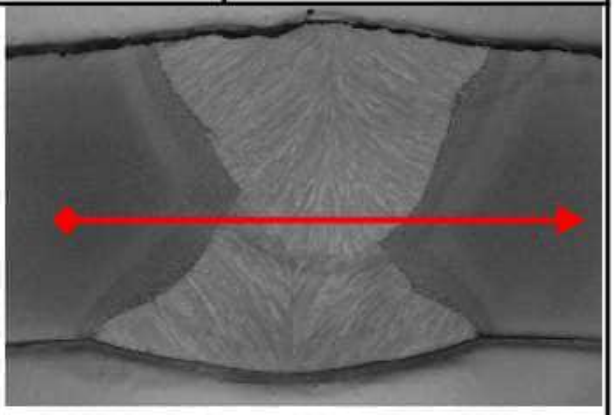
Metallographie und Elektronenmikroskopie

Order number	9039784000
Sample description	5.2; Center
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	
☑ HV **10**	DIN EN ISO 6507-1:2018-07
☐ HBW	DIN EN ISO 6506-1:2015-02
☐ HRC	DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C	



Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:		237 HV 10
Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	285,0	295,8	0,2904	220	212		BM 1
2	285,2	301,8	0,2935	215			
3	290,8	304,3	0,2975	209			
4	293,3	302,8	0,2981	209			
5	293,3	303,9	0,2986	208			
1	290,4	293,9	0,2921	217	221		HAZ 1
2	286,6	282,9	0,2848	229			
3	284,4	284,6	0,2845	229			
4	292,7	295,8	0,2942	214			
5	293,1	292,7	0,2929	216			
1	280,8	280,2	0,2805	236	234		WM
2	284,4	281,3	0,2828	232			
3	282,3	282,9	0,2826	232			
4	280,4	278,3	0,2794	238			
5	283,3	278,8	0,2810	235			
1	294,3	292,7	0,2935	215	221		HAZ 2
2	289,5	290,8	0,2902	220			
3	286,4	291,6	0,2890	222			
4	290,6	286,0	0,2883	223			
5	285,4	288,9	0,2872	225			
1	295,2	307,6	0,3014	204	207		BM 2
2	296,6	304,3	0,3005	205			
3	293,5	306,6	0,3000	206			
4	292,9	304,5	0,2987	208			
5	289,8	301,0	0,2954	213			

Date: 06.11.22

Tester: Scheck

Figure 3.112: Hardness measurements of GRS550/X80 (5)

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Hardness test

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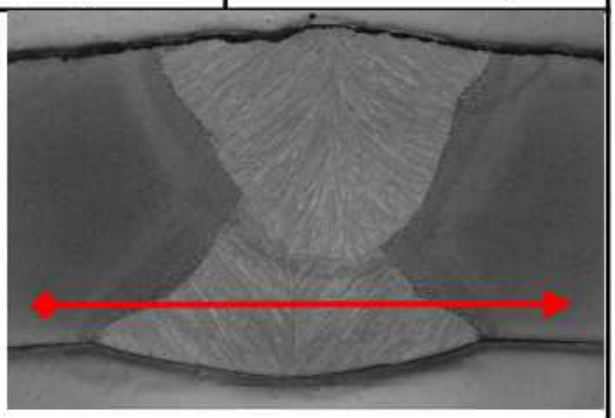

Order number	9039784000
Sample description	5.2; **Root**
Administrator	Silcher
Test instrument	Zwick Z 323 (neu)
Serial number	H2932-002-50430
Test conditions	

☑ HV **10** DIN EN ISO 6507-1:2018-07
☐ HBW DIN EN ISO 6506-1:2015-02
☐ HRC DIN EN ISO 6508-1:2016-12
☐ Test temperatur, if outside (23+/-5) °C

Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV	Reference:	237 HV 10

Indentation no.	d_1 µm	d_2 µm	d_m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	293,1	302,0	0,2975	209	209		BM 1
2	297,0	301,8	0,2994	207			
3	295,4	304,3	0,2998	206			
4	291,4	299,9	0,2957	212			
5	293,3	302,0	0,2977	209			
1	282,3	288,1	0,2852	228	227		HAZ 1
2	276,1	283,1	0,2796	237			
3	285,6	291,4	0,2885	223			
4	283,7	292,2	0,2880	224			
5	287,1	290,8	0,2889	222			
1	282,9	284,0	0,2834	231	245		WM
2	279,2	276,5	0,2778	240			
3	276,3	275,8	0,2761	243			
4	270,2	270,9	0,2706	253			
5	269,4	269,6	0,2695	255			
1	278,8	276,9	0,2778	240	244		HAZ 2
2	263,2	268,8	0,2660	262			
3	275,0	276,5	0,2758	244			
4	274,8	279,2	0,2770	242			
5	282,1	284,2	0,2831	231			
1	298,5	306,2	0,3023	203	208		BM 2
2	296,4	305,7	0,3011	205			
3	294,3	303,9	0,2991	207			
4	288,3	299,9	0,2941	214			
5	293,3	303,5	0,2984	208			

Date: 06.11.22

Tester: Scheck

Figure 3.113: Hardness measurements of GRS550/X80 (6)

3.25 L415

The samples were taken from a longitudinally welded pipe bend with a diameter of 660 mm and a wall thickness of 11.1 mm.

The relevant material-specific data is as follows:

Table 3.78: Characteristics of L415

Production year	2020	
Production standard	EN ISO 3183	
Specific minimum characteristics	R_e [MPa]	415
	R_m [MPa]	520
	K_v [J]	27
Material characteristics	R_e [MPa]	468
	R_m [MPa]	618
	K_v [J]	192

Table 3.79: Chemical composition of L415

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.098	0.254	1.369	0.016	0.0013	0.017	0.041	0.108
	Ni	V	Ti	Nb				
	0.35	0.002	0.003	0.022				

Table 3.80: Fracture toughness of L415

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
L415	Base material	9	108.5
L415	Weld material	9	138.4

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Samples were taken from the following areas:

- base material
- weld material of the longitudinal weld

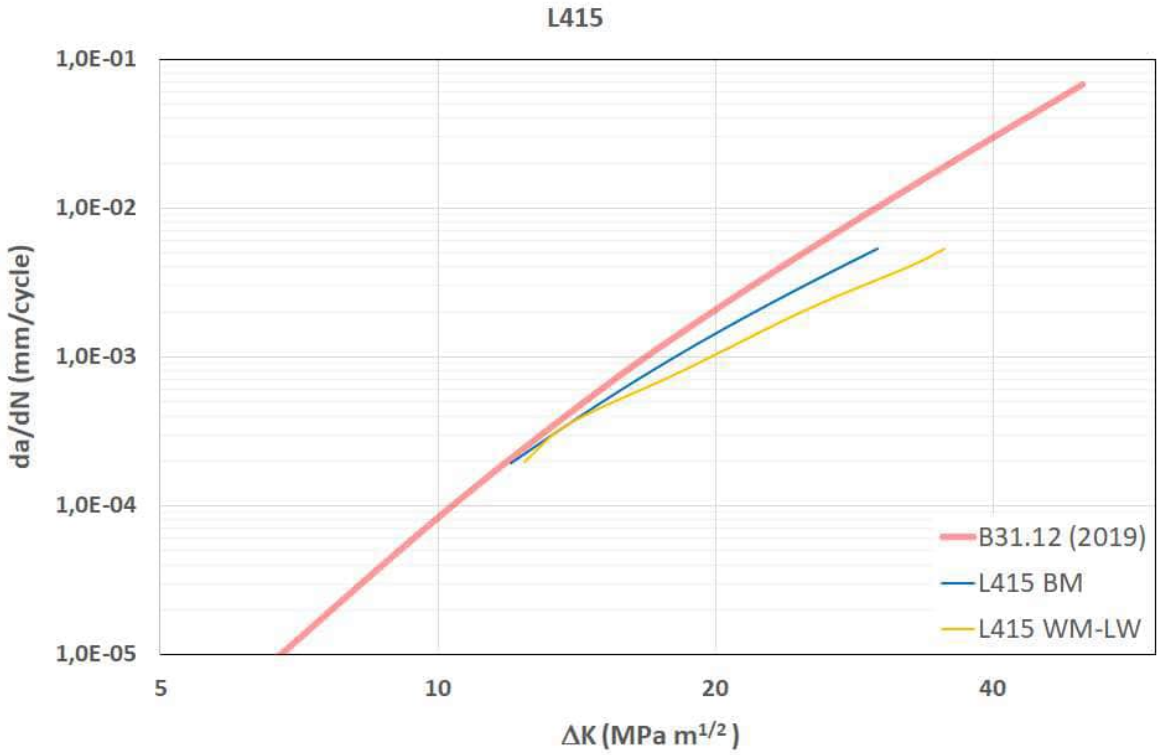

Figure 3.114: Crack growth L415

3.26 P355 NL1

The samples were taken from a seamless steel pipe with a diameter of 368 mm and a wall thickness of 37 mm.

The relevant material-specific data is as follows:

Table 3.81: Characteristics of P355 NL1

Production year	2013	
Production standard	API Spec. 5L (2013) / EN 10216-3	
Specific minimum characteristics	R_e [MPa]	345
	R_m [MPa]	490
	K_v [J]	43
Material characteristics	R_e [MPa]	365
	R_m [MPa]	529
	K_v [23] [J]	224

Table 3.82: Chemical composition of P355 NL1

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.15	0.2	1.3	0.1	0.002	0.14	0.12	0.04
	Ni	V	Ti	Nb				
		0.05	0.001	0.013				

Table 3.83: Fracture toughness of P355 NL1

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
P355 NL1	Base material	15	111.6

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[23] Sample form as per ASTM A 370 transverse at 0°C

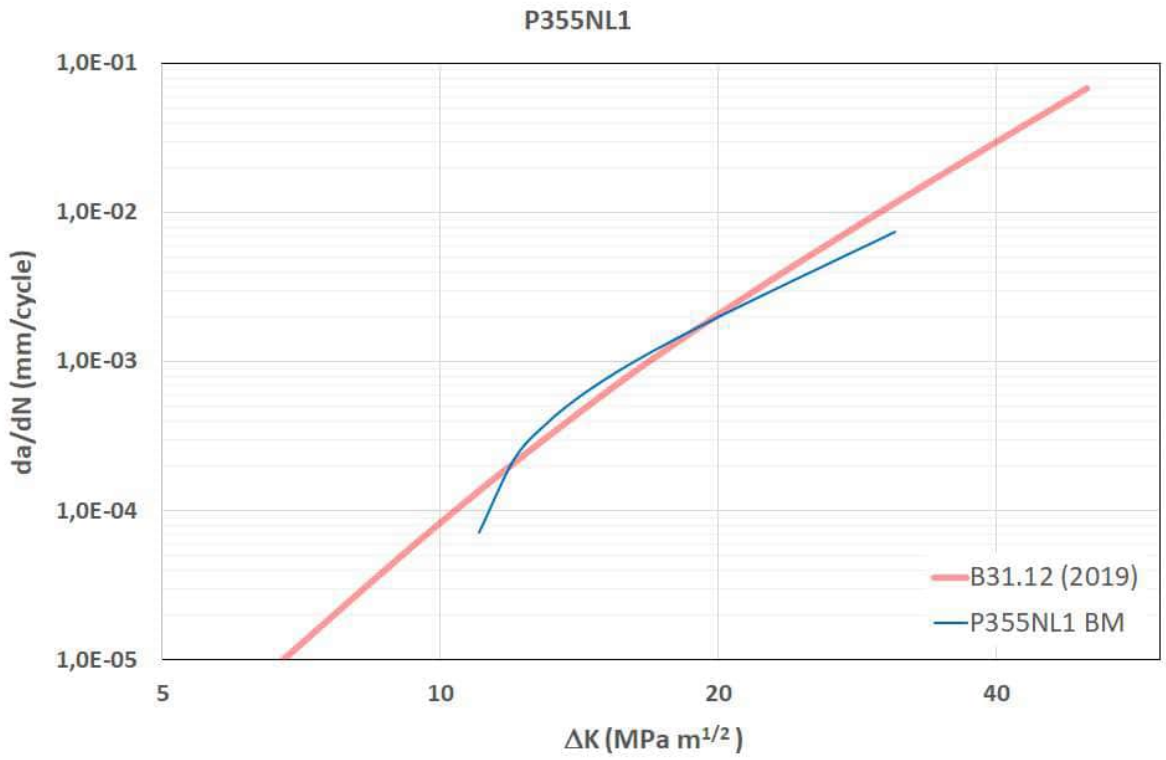

Figure 3.115: Crack growth in P355 NL1

3.27 GJS400

GJS400 (spheroidal graphite) is sometimes used in the pressure vessels of valves. The sample used involves a casting sample.

The relevant material-specific data is as follows:

Table 3.84: Characteristics of GJS400

Production year	2022	
Production standard	EN 1563	
Specific minimum characteristics	R_e [MPa]	240
	R_m [MPa]	370
	K_v [J]	14
Material characteristics	R_e [MPa]	294
	R_m [MPa]	421
	K_v [24] [J]	15

Table 3.85: Chemical composition of GJS400

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	3.822				0.0038			
	Ni	V	Ti	Nb				

Table 3.86: Fracture toughness of GJS400

Material	Location	Item no.	K_{JIc} [MPa$\sqrt{m}$]
GJS400	Base material	14	62.2

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[24] Notched-bar impact test as per DIN EN ISO 148-1; notch form: KV2; test temperature: 0 °C

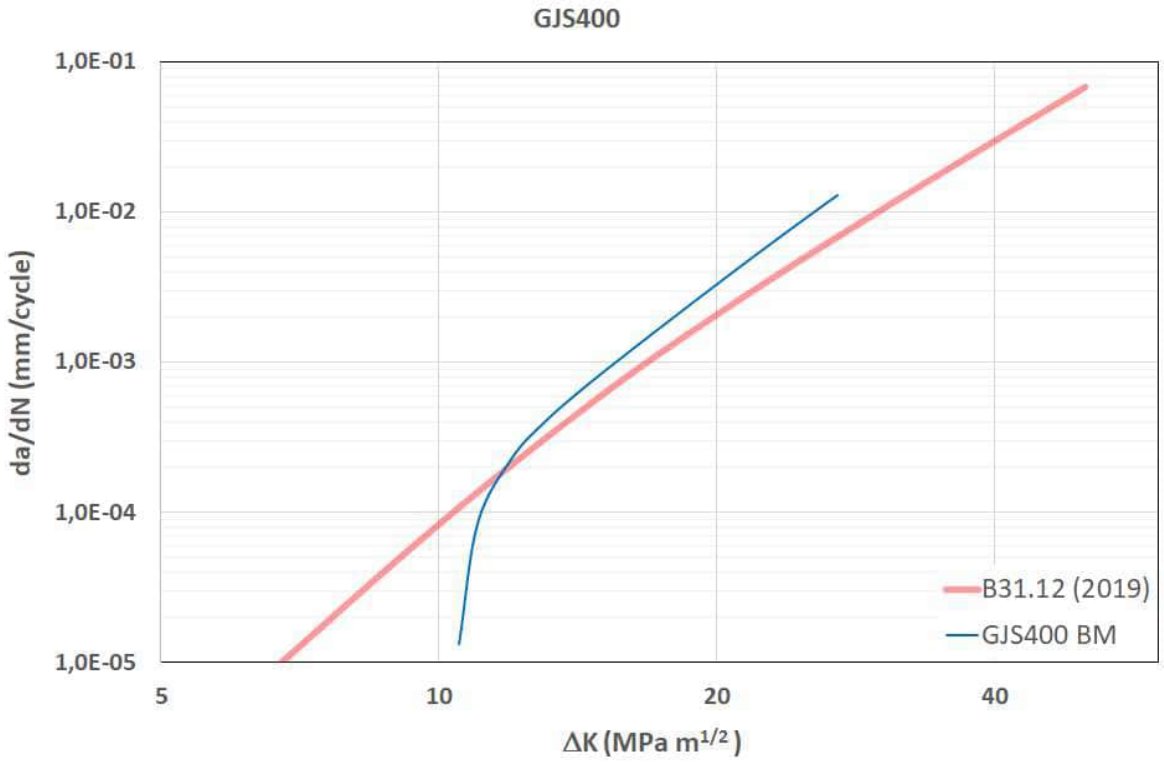

Figure 3.116: Crack growth GJS400

3.28 P460 QL1

P460 QL1 (cast steel) is also used in valve pressure vessels. The sample has a thickness of 50 mm.

The relevant material-specific data is as follows:

Table 3.87: Characteristics of P460 QL1

Production year	2019	
Production standard	EN 10028-6 (2017)	
Specific minimum characteristics	R_e [MPa]	460
	R_m [MPa]	550
	K_v [J]	27
Material characteristics	R_e [MPa]	464
	R_m [MPa]	562
	K_v [25] [J]	282

Table 3.88: Chemical composition of P460 QL1

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.081	0.376	1.35	0.007	0.0005	0.159	0.058	0.087
	Ni	V	Ti	Nb				
	0.27	0.05	0.002	0.018				

Table 3.89: Fracture toughness of P460 QL1

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
P460 QL1	Base material	16	118.6

The curves describing crack growth in a hydrogen atmosphere are shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[25] Notched-bar impact test as per DIN EN ISO 148-1 at -60 °C, form: CV

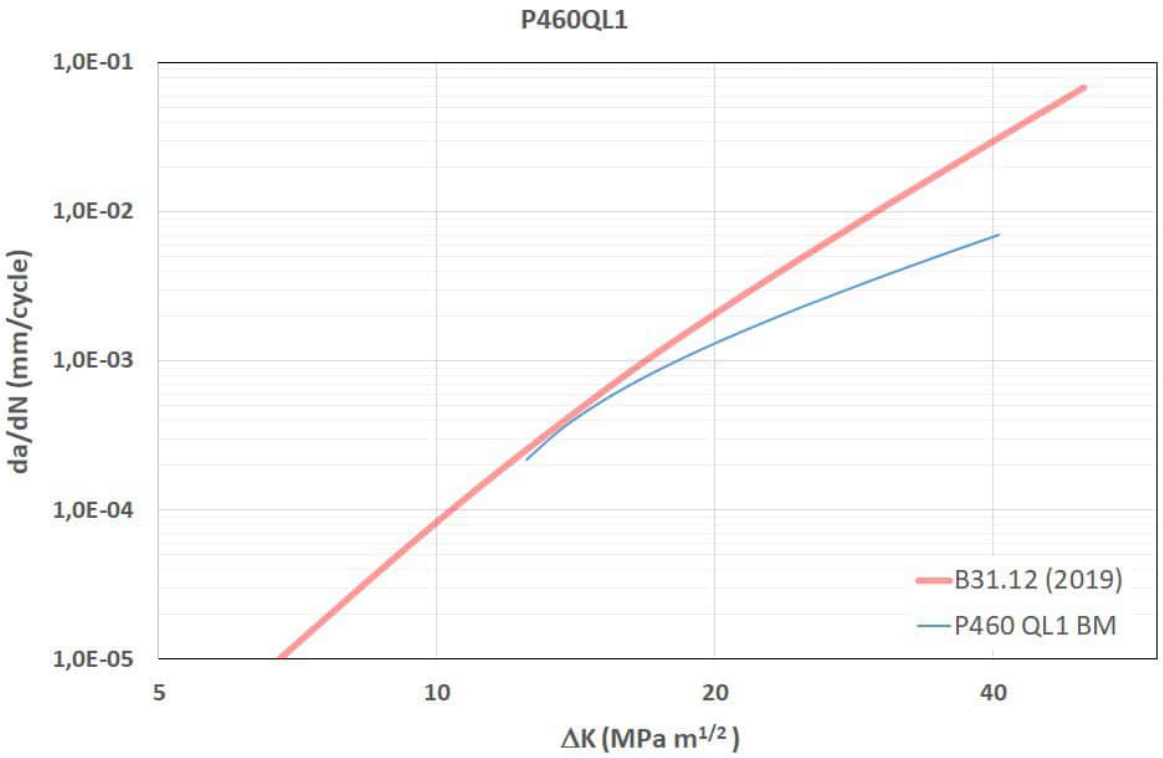

Figure 3.117: Crack growth P460 QL1

3.29 C22.3

The samples were taken from a plate with a thickness of 20 mm.

The relevant material-specific data is as follows:

Table 3.90: Characteristics of C22.3

Production year	2022	
Production standard	WB364	
Specific minimum characteristics	R_e [MPa]	240
	R_m [MPa]	410
	K_v [26][J]	31
Material characteristics	R_e [MPa]	347
	R_m [MPa]	490
	K_v [27] [J]	94

Table 3.91: Chemical composition of C22.3

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.16	0.154	0.741	0.026	0.012	0.027	0.017	0.005
	Ni	V	Ti	Nb				
	0.001	0.001	0.001	0.001				

Table 3.92: Fracture toughness of C22.3

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
C22.3	Base material	44	104.1

The curve describing crack growth in a hydrogen atmosphere is shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[26] Notched-bar impact test as per DIN EN ISO 148-1 (2017-05), notch form: KV2; test temperature: 20 °C
[27] Notched-bar impact test as per DIN EN ISO 148-1 (2017-05); notch form: KV2; test temperature: 0 °C

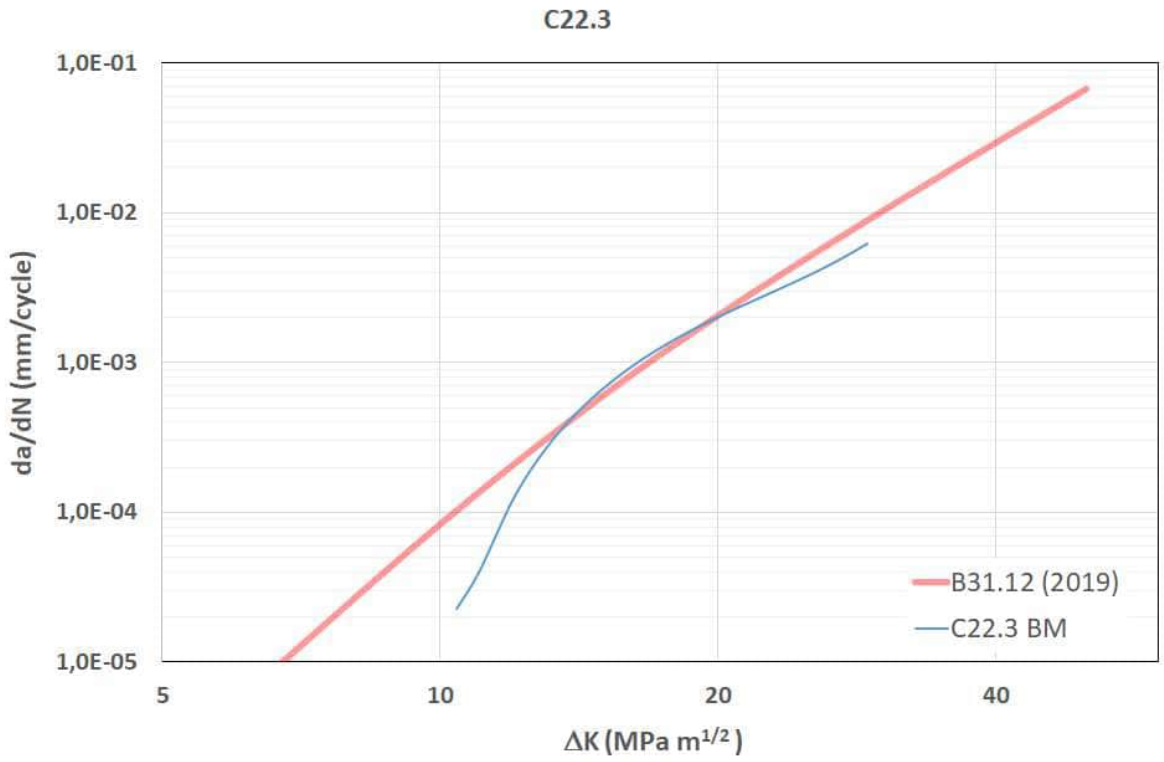

Figure 3.118: Crack growth C22.3

3.30 GS C25 N

The sample was taken from a valve housing.

The relevant material-specific data is as follows:

Table 3.93: Characteristics of GS C25 N

Production year	1993	
Production standard	DIN 17245	
Specific minimum characteristics	R_e [MPa]	245
	R_m [MPa]	440
	K_v [J]	27
Material characteristics	R_e [MPa]	311
	R_m [MPa]	472
	K_v [28] [J]	18

Table 3.94: Chemical composition of GS C25 N

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.2	0.403	0.678	0.035	0.014	0.234	0.235	0.059
	Ni	V	Ti	Nb				
	0.136	0.001	0.003	0.001				

Table 3.95: Fracture toughness of GS C25 N

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
GS C25 N	Base material	46	111.6

The curve describing crack growth in a hydrogen atmosphere is shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[28] Notched-bar impact test as per DIN EN ISO 148-1 (2017); sample form: KV2; test temperature: 0 °C; longitudinal

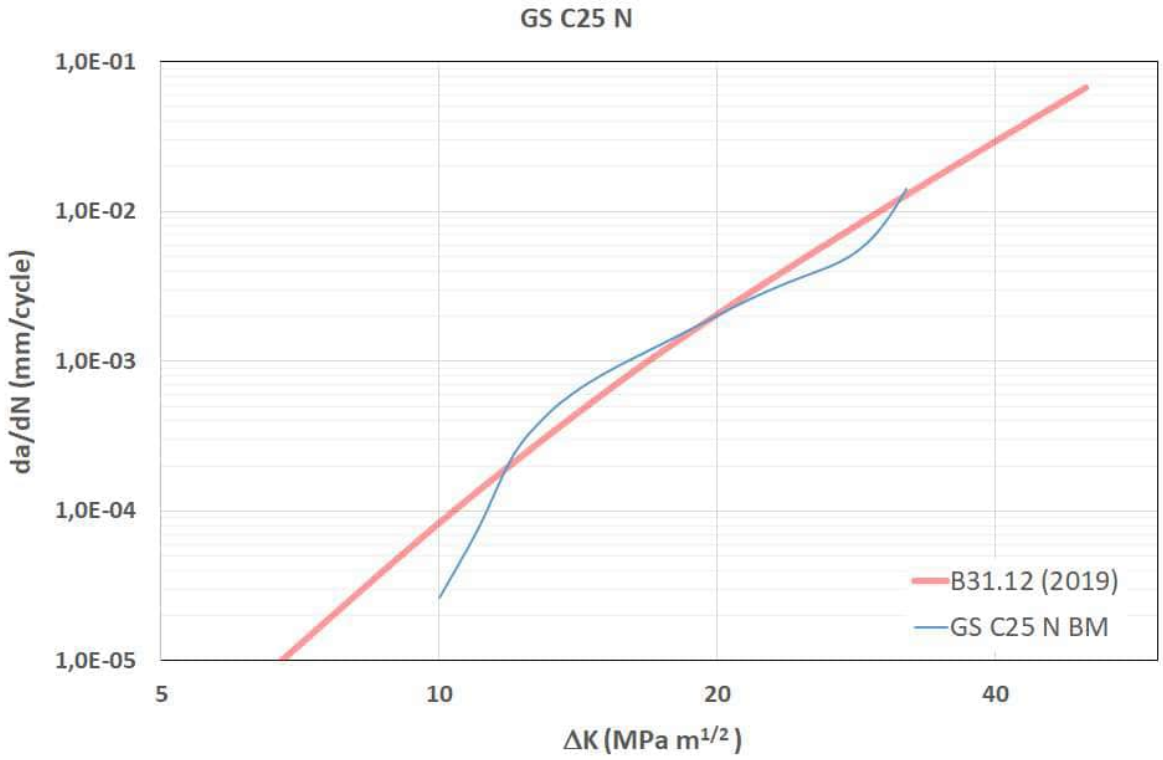

Figure 3.119: Crack growth GS C25 N

3.31 TStE 355N

The samples were taken from a plate with a thickness of 20 mm.

The relevant material-specific data is as follows:

Table 3.96: Characteristics of TStE 355N

Production year	2002	
Production standard	DIN 17102	
Specific minimum characteristics	R_e [MPa]	355
	R_m [MPa]	490
	K_v [24][J]	55
Material characteristics	R_e [MPa]	434
	R_m [MPa]	530
	K_v [29] [J]	281

Table 3.97: Chemical composition of TStE 355N

Chemical composition [%]	C	Si	Mn	P	S	Cu	Cr	Mo
	0.14	0.201	1.311	0.017	0.007	0.088	0.094	0.022
	Ni	V	Ti	Nb				
	0.039	0.025	0.003	0.03				

Table 3.98: Fracture toughness of TStE 355N

Material	Location	Item no.	K_{Jlc} [MPa$\sqrt{m}$]
TStE 355N	Base material	45	133.3

The curve describing crack growth in a hydrogen atmosphere is shown below. Crack growth was investigated at an overpressure of 100 bar, a frequency of 1 Hz and an R value of 0.5.

Only the base material was investigated.

[29]Notched-bar impact test as per DIN EN ISO 148-1 (2017); sample form: KV2; test temperature: 0 °C; longitudinal

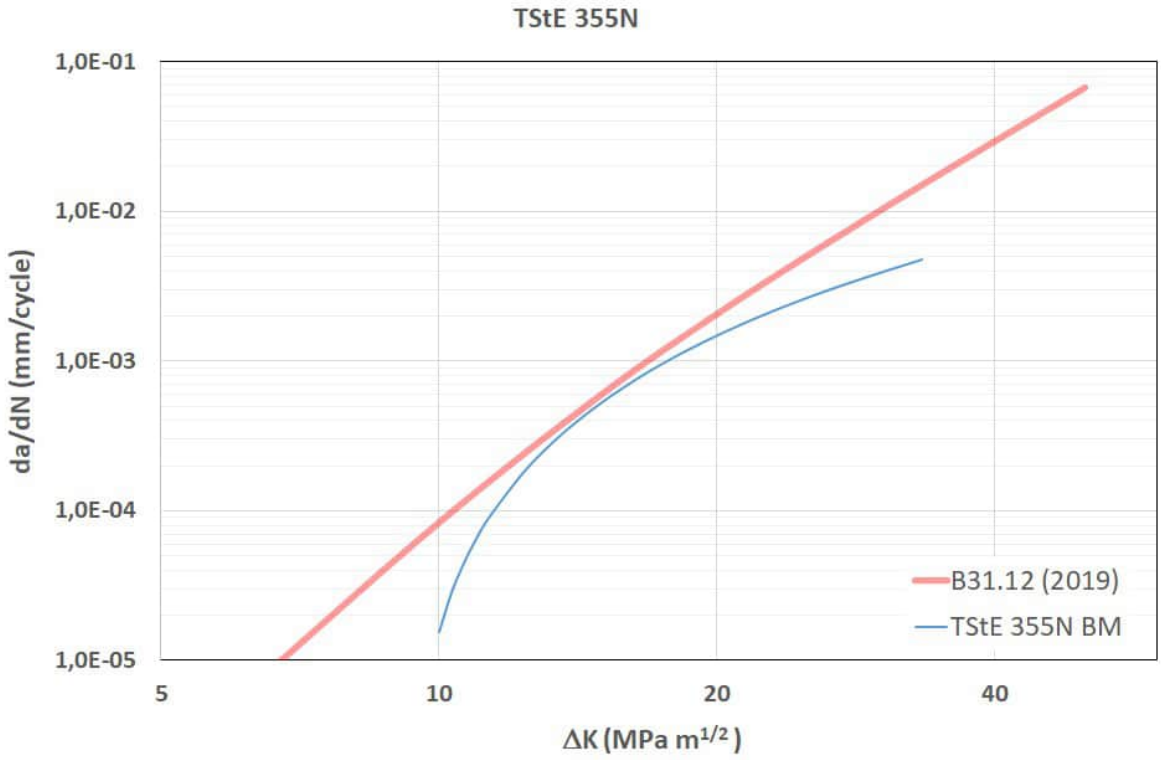

Figure 3.120: Crack growth TStE 355N

4 Results of Crack Growth Measurements

4.1 Crack Growth at p_{H2} = 100 bar and R=0.5

As was the case with the static tests, the cyclical fracture-mechanical tests were performed on the majority of samples at a constant hydrogen pressure of p_{H2} = 100 bar. In conformance with the underlying test parameters in line with [3] and [7], the test frequency was set to f = 1 Hz and the stress ratio to R = 0.5.

Figure 4.1 shows the results of the cyclical crack growth tests for the base material, the weld and the heat-affected zone of the weld of the investigated materials. For purposes of comparison, the crack growth relationship as defined by ASME B 31.12 is also plotted as a red line.

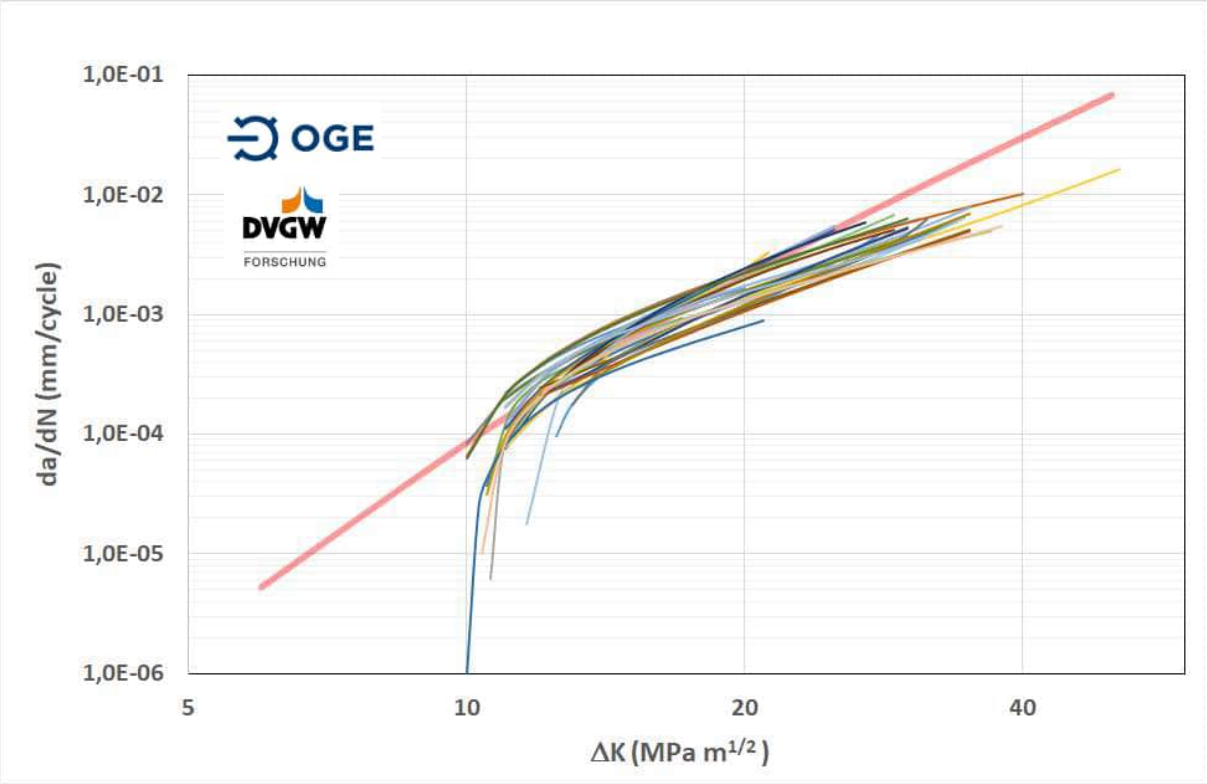

Figure 4.1: Established crack growth of the investigated materials in hydrogen (100 bar, R = 0.5)

During testing, the crack growth rates were established in the range of stress intensities ΔK of approx. 10 to approx. 40 MPa $m^{1/2}$. However, the tests performed did not focus on establishing the lower threshold value (ΔK_{th}). Knowledge of very low stress intensities is not so important in connection with predictions for a gas pipeline's service life since low stress intensities have practically no influence on the results of these predictions.

In concurrence with the investigations performed in the USA, the measured crack growth curves principally form a relatively homogenous range below the crack growth relationship as defined by ASME B 31.12, although very different materials were tested in terms of strength, microstructure and ductility.

In a more precise comparison with the crack growth relationship as defined by ASME B 31.12, the crack growth measured in this project tends to be slightly higher for lower stress intensities and the crack growth relationship is lower for higher stress intensities.

Hence, by dividing the crack growth law into two bilinear areas (Figure 4.2), a more precise, conservative approach to the measurement data can be obtained. This usual procedure was already suggested in [8], for example.

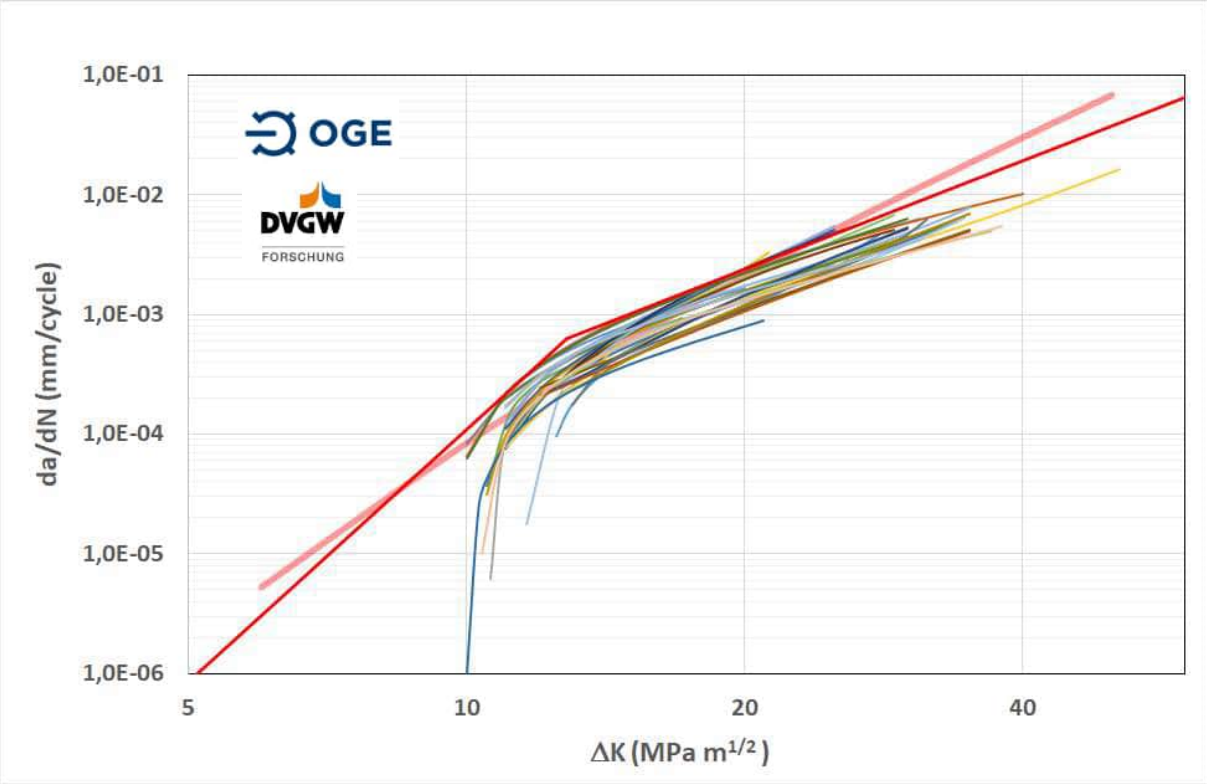

Figure 4.2: Conservative description of the established crack growth in hydrogen for p_{H2} = 100 bar and R = 0.5

The following crack growth law was derived on the basis of the established test data for p_{H2}=100 bar and R=0.5:

for $\Delta K \leq 12.851\ MPa\sqrt{m}$ $\quad \frac{da}{dN} = 1.1 \cdot 10^{-11} \cdot \Delta K^7$

for $\Delta K \geq 12.851\ MPa\sqrt{m}$ $\quad \frac{da}{dN} = 3 \cdot 10^{-7} \cdot \Delta K^3$

p_{H2} [bar] ; ΔK [MPa $m^{0.5}$] ; da/dN [mm/load cycle]

4.2 Crack Growth Law Depending on Hydrogen Pressure p_{H2}

Figures 4.3 to 4.5 show the results of crack growth measurements of the materials St35 and L485 which were performed at hydrogen pressures of p_{H2} = 0.2 bar to p_{H2} = 100 bar. It was revealed that crack growth, particularly for lower stress intensities and lower hydrogen pressures, initially behaves similar to crack growth in air. If cyclical stress intensity increases, crack growth approaches the typical crack growth for higher pressures or for $p_{H2} \approx 100$ bar. When applying the bilinear crack growth law as shown in Figure 4.2, this behaviour can be approximately described by taking into consideration a pressure dependence in the crack growth relationship for lower stress intensities. For higher stress intensities, it is assumed that the crack growth relationship is independent of hydrogen pressure and thus corresponds to behaviour at p_{H2} = 100 bar. This procedure was also already suggested in [8] and checked for applicability to the data presented here.

In Figures 4.3 to 4.5, the exemplary description of crack growth for the corresponding hydrogen pressures is shown in the form of bilinear straight lines in the same colour as the relevant measurement.

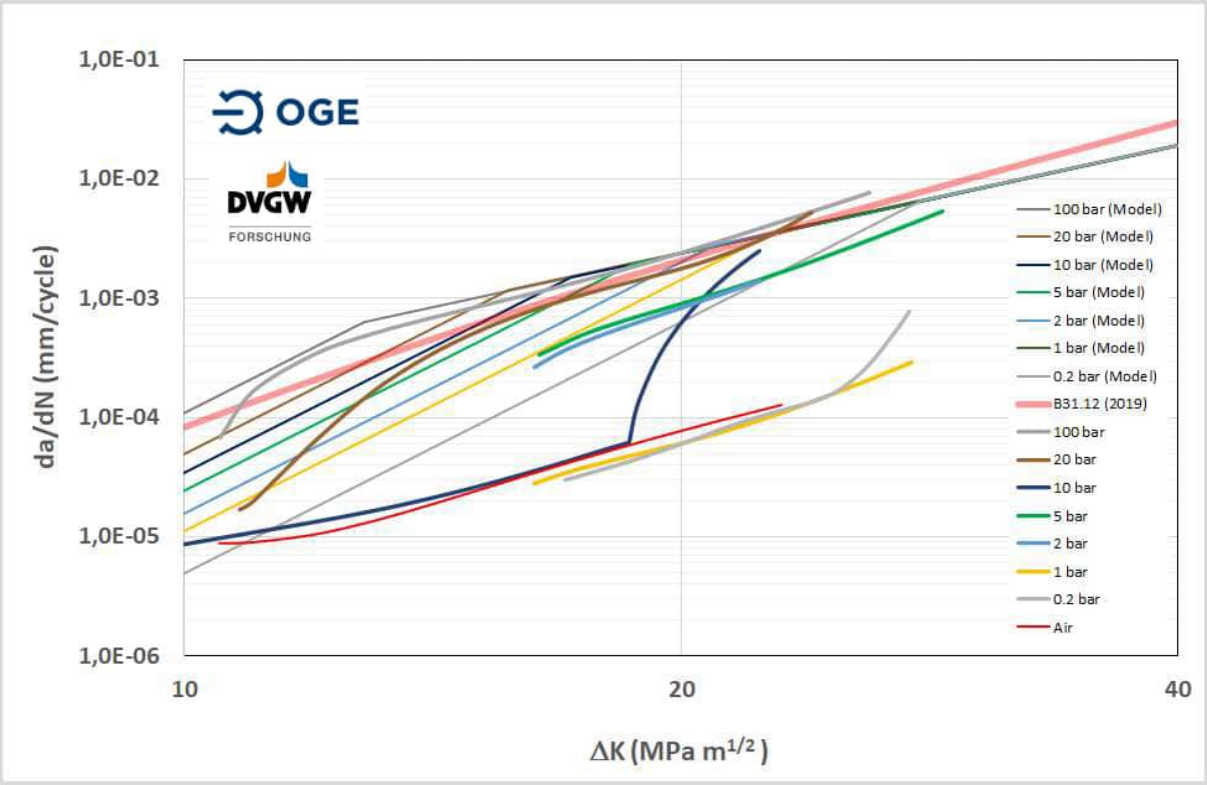

Figure 4.3: Crack growth in hydrogen for different hydrogen pressures and bilinear model (St35, item no. 25ff at R = 0.5)

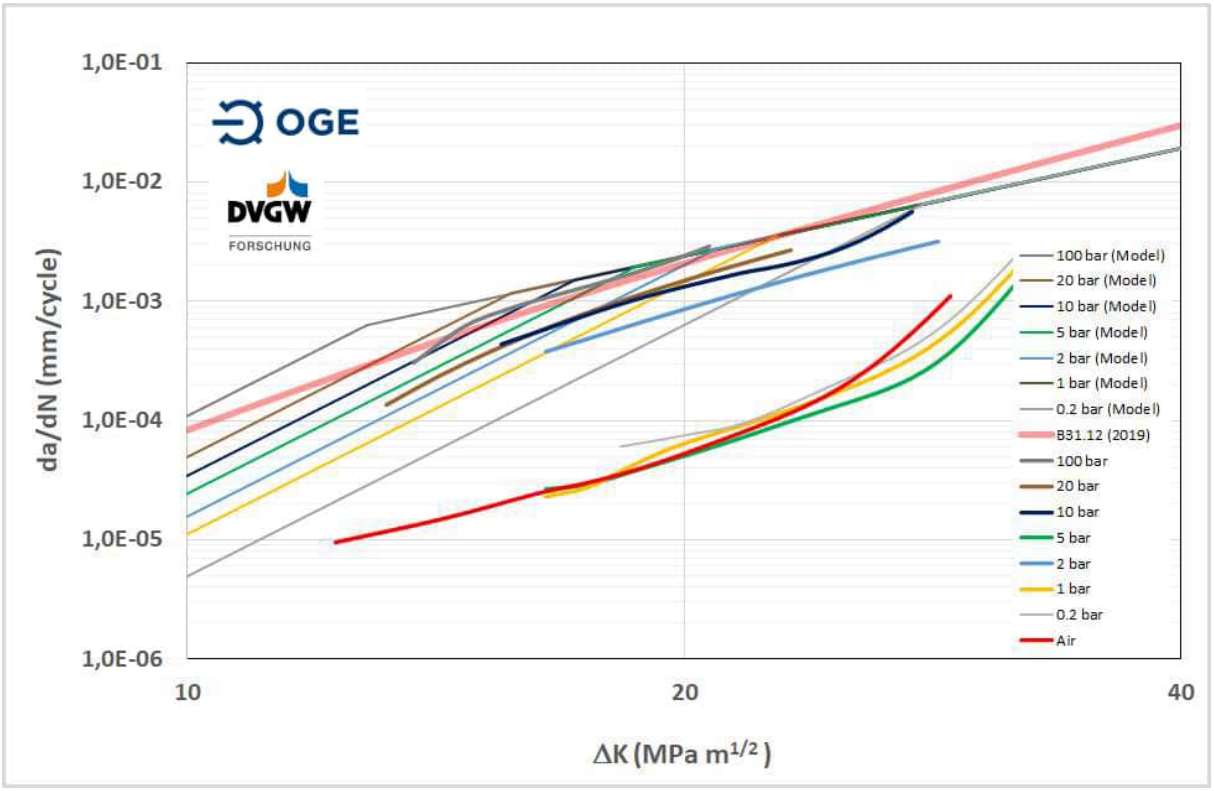

Figure 4.4: Crack growth in hydrogen for different hydrogen pressures and bilinear model (St35, item no. 41 at R = 0.5)

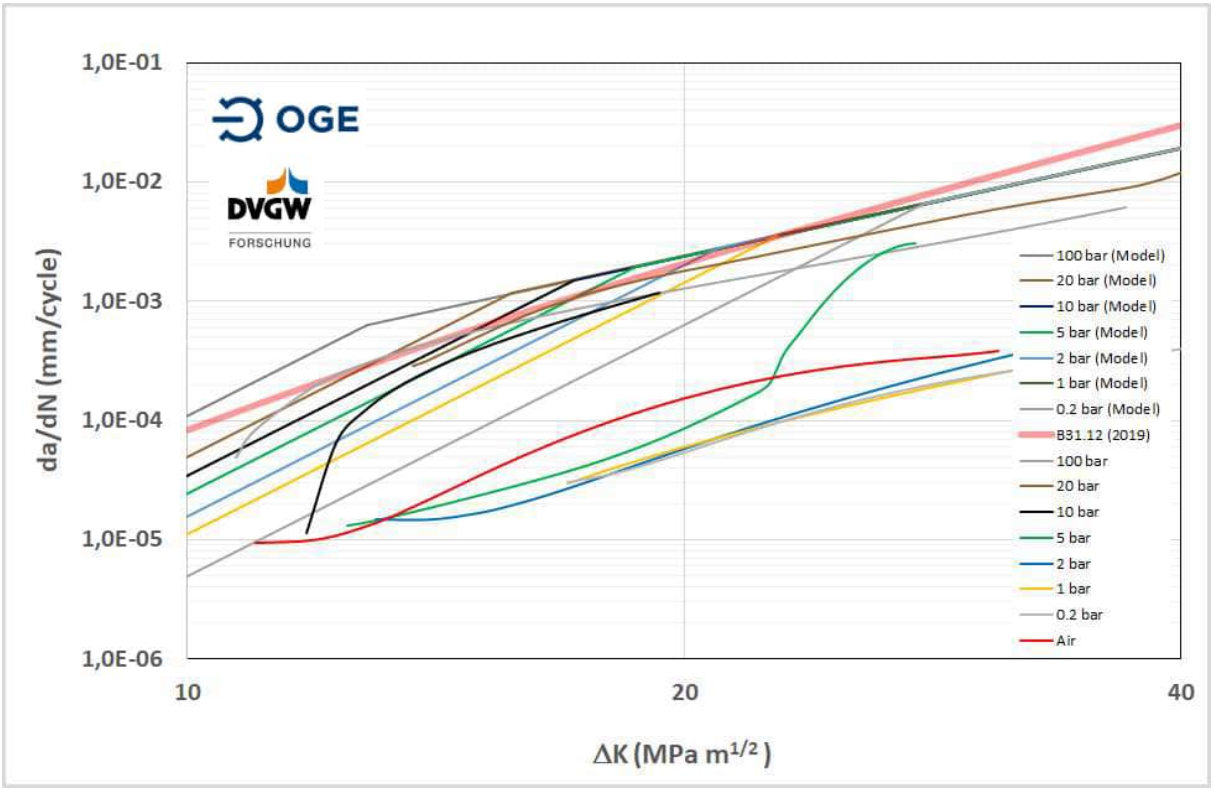

Figure 4.5: Crack growth in hydrogen for different hydrogen pressures and bilinear model (L485, item no. 32ff at R = 0.5)

A more precise analysis of crack growth behaviour for different hydrogen pressures p_{H2} reveals the following:

- At lower stress intensities and hydrogen pressures, crack growth is comparable with crack growth in air / natural gas.
- At higher hydrogen pressures, crack growth very rapidly approaches the behaviour at p_{H2} = 100 bar, already at lower stress intensities.
- The position of the transitional area from “slow” crack growth to H_2-typical rapid crack growth depends on the hydrogen pressure, although it cannot be predicted exactly.

Measurements on L485 (Figure 4.5) show, for example, a crack growth which is comparable to that in air within the entire measured range of stress intensities for pressures of p_{H2} = 0.2 bar to p_{H2} = 2 bar. At a pressure of p_{H2} = 5 bar, the crack growth rate above stress intensities of ΔK > 22 MPa $m^{0.5}$ approaches the typical crack growth rate in hydrogen. At a hydrogen pressure of p_{H2} = 10 bar, the transition towards a high crack growth rate starts already at stress intensities of $\Delta K \approx$ 12 MPa $m^{0.5}$.

Measurements on St35 (Figures 4.3 to 4.4) also show a crack growth behaviour which corresponds to that in air for low hydrogen pressures of p_{H2} = 0.2 bar and p_{H2} = 1 bar (in one case even for p_{H2}= 5 bar) for all investigated stress intensities ΔK. However, crack growth for the same stress intensity at p_{H2} = 2 bar was greater than at p_{H2} = 5 bar (see Figure 4.4) or at p_{H2} = 10 bar partially lower than at p_{H2} = 2 – 5 bar (see Figure 4.3).

Hence, the influencing factors which determine the dependence of crack growth with regard to the hydrogen pressure level appear to be very complex and are probably governed by the locally existing microstructures of the materials involved.

Within the context of applying a conservative safety concept, it is, however, helpful to introduce a conservative estimate of crack growth.

The established test data results in a conservative description of crack growth for R=0.5:

for $\Delta K \leq \left[3.6667 \cdot 10^{-6}\sqrt{p_{H2}}\right]^{-0,25} MPa\sqrt{m}$ $\qquad \frac{da}{dN} = 1.1 \cdot 10^{-12} \cdot \Delta K^7 \cdot \sqrt{p_{H_2}}$

for $\Delta K \geq \left[3.6667 \cdot 10^{-6}\sqrt{p_{H2}}\right]^{-0,25} MPa\sqrt{m}$ $\qquad \frac{da}{dN} = 3 \cdot 10^{-7} \cdot \Delta K^3$

p_{H2} [bar] ; ΔK [MPa $m^{0.5}$] ; da/dN [mm/load cycle]

Note: The given equations contain the equations specified in Section 4.1.

4.3 Additional Consideration of Mean Stress (R Value)

ASME standard [9] contains a suggestion for converting crack growth behaviour to any R values insofar as the relevant tests have been performed at a constant R value. Figures 4.6 and 4.7 show a comparison of the measured crack growth curves as calculated in line with [9] for R = 0.1 and R = 0.7, assuming that these curves have been calculated from the measured curves for R = 0.5.

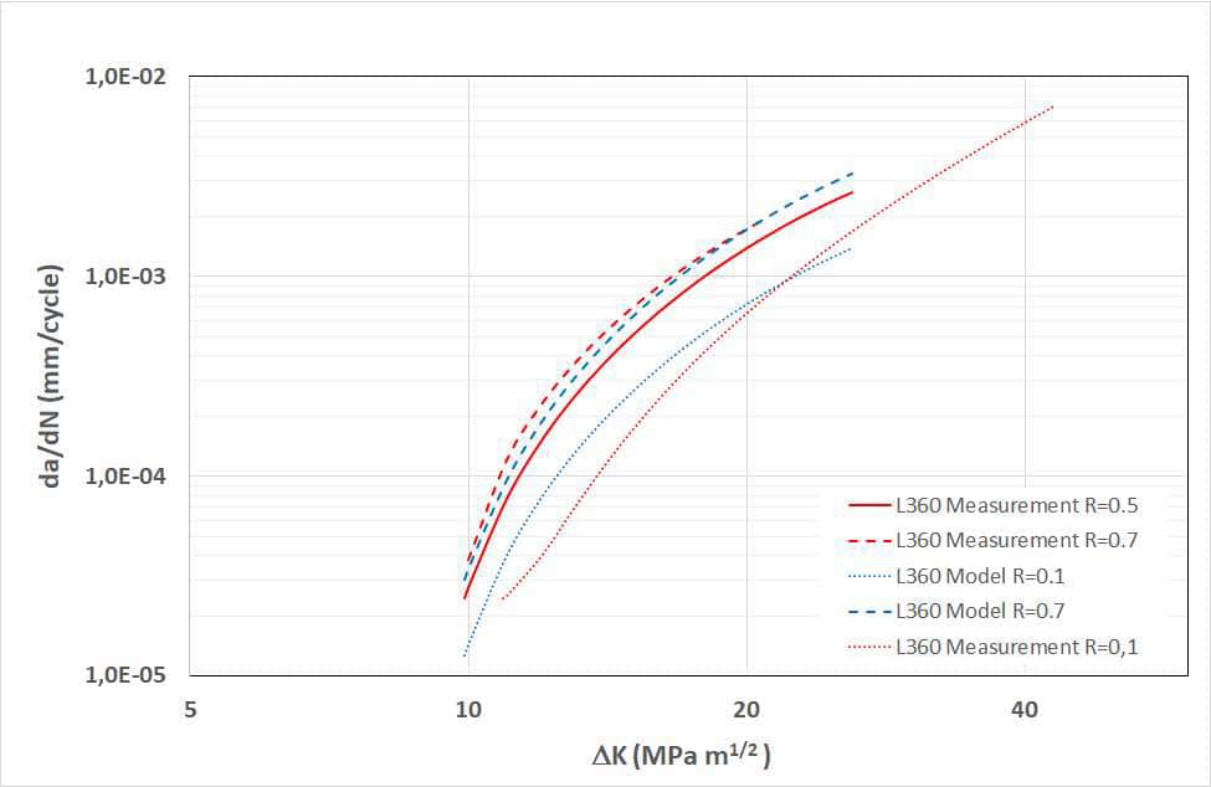

Figure 4.6: Calculated and measured impact of the R value on crack growth behaviour (L360, R = 0.1, R = 0.5, R = 0.7 p_{H2} =100 bar)

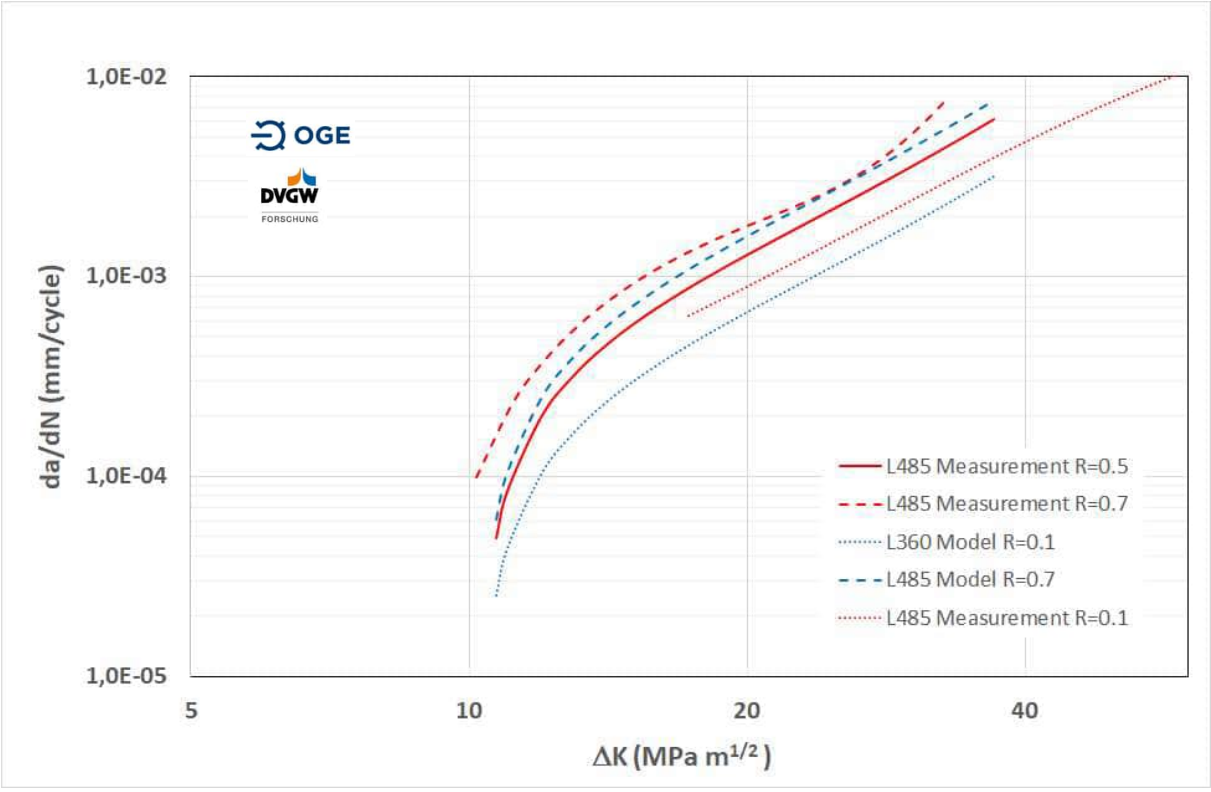

Figure 4.7: Calculated and measured impact of the R value on crack growth behaviour (L485, R = 0.1, R = 0.5, R = 0.7 p_{H2} =100 bar)

For both materials, the curves calculated for R = 0.7 highly correspond to the actually measured crack growth curves. For R = 0.1, concurrence between the calculated and measured curves may be described as sufficiently accurate, within the context of usage in service life estimates.

For the purpose of illustrating the impact of the R value on the bilinear crack growth law applied here, the R values (for R = 0.1 and R = 0.7) are plotted in Figure 4.8 as dotted red lines.

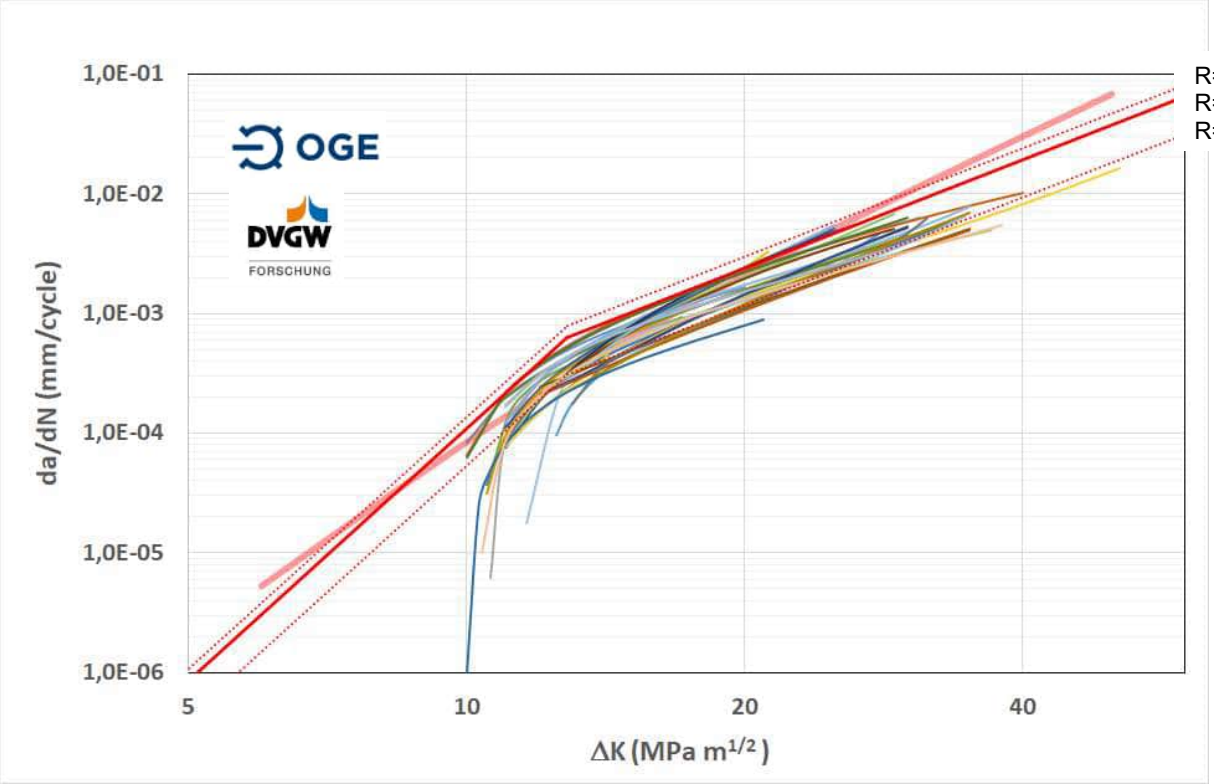

Figure 4.8: Bilinear crack growth law for R=0.1, R=0.5 and R=0.7 (p_{H2} =100 bar)

The following crack growth law was derived on the basis of the established test data:

for $\Delta K \leq \left[3.6667 \cdot 10^{-6}\sqrt{p_{H2}}\right]^{-0,25} MPa\sqrt{m}$ $\quad \frac{da}{dN} = 4.4 \cdot 10^{-13} \cdot (1 + 3 \cdot R) \cdot \Delta K^7 \cdot \sqrt{p_{H_2}}$

for $\Delta K \geq \left[3.6667 \cdot 10^{-6}\sqrt{p_{H2}}\right]^{-0,25} MPa\sqrt{m}$ $\quad \frac{da}{dN} = 1.2 \cdot 10^{-7} \cdot (1 + 3 \cdot R) \cdot \Delta K^3$

p_{H2} [bar] ; ΔK [MPa $m^{0.5}$] ; da/dN [mm/load cycle]

Note: The given equations contain the equations specified in Sections 4.1 and 4.2.

5 Selected Results for Fracture Toughness

5.1 Results for p_{H2} = 100 bar

Figures 5.1 to 5.4 show an overview of the results for fracture toughness K_{Ic} at a test pressure of p_{H2} = 100 bar. The data indicated in “blue” refers to tests performed on the base materials, whereas the “red” data relates to tests on welds and heat-affected zones. The minimum value stipulated by the codes of practice (K_{Ic} = 55 MPa $m^{½}$) is also indicated.

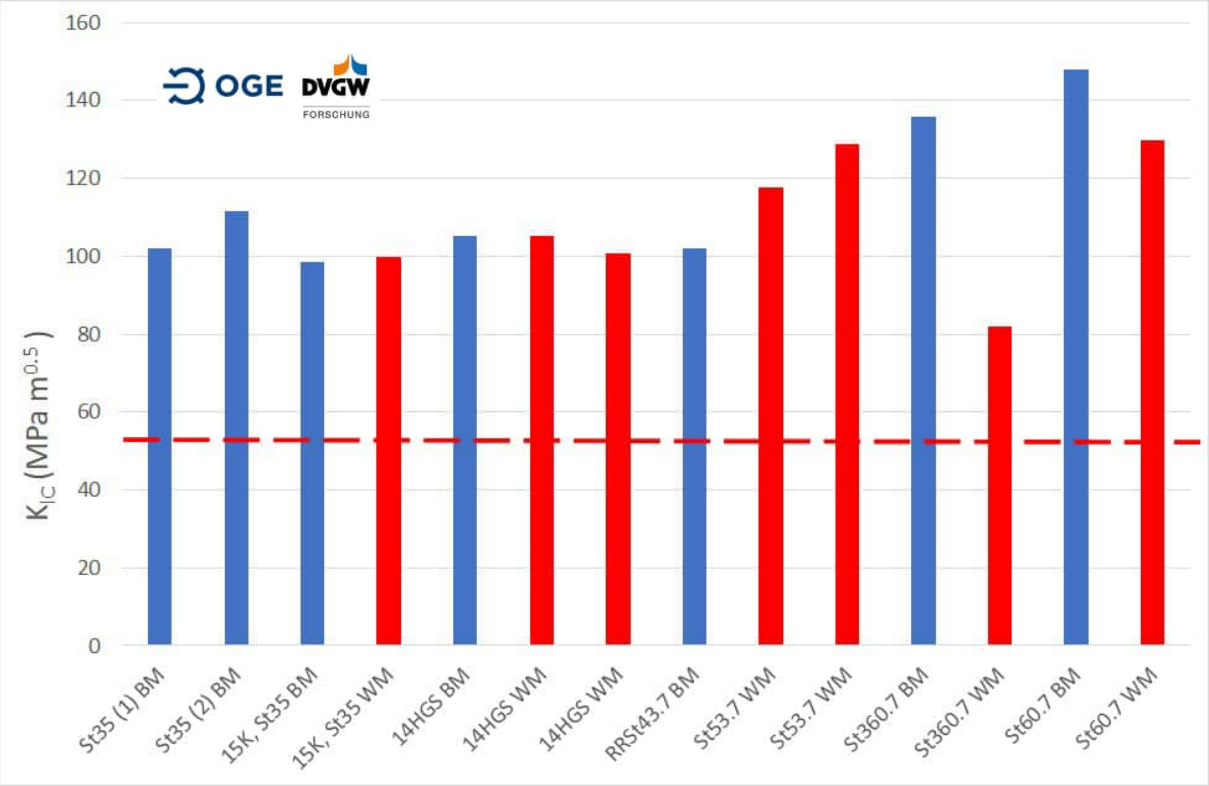

Figure 5.1: Established fracture toughness (K_{Ic}) for the tested pipeline materials (1)

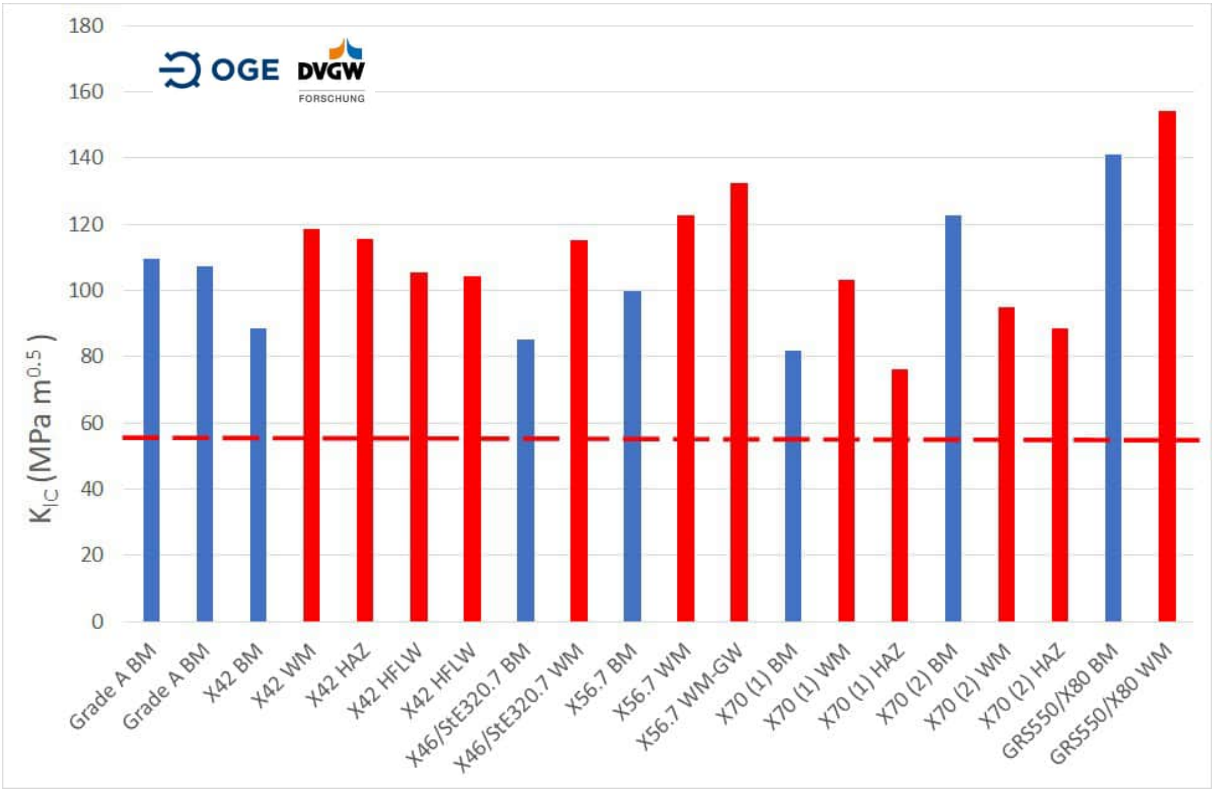

Figure 5.2: Established fracture toughness (K_{Ic}) for the tested pipeline materials (2)

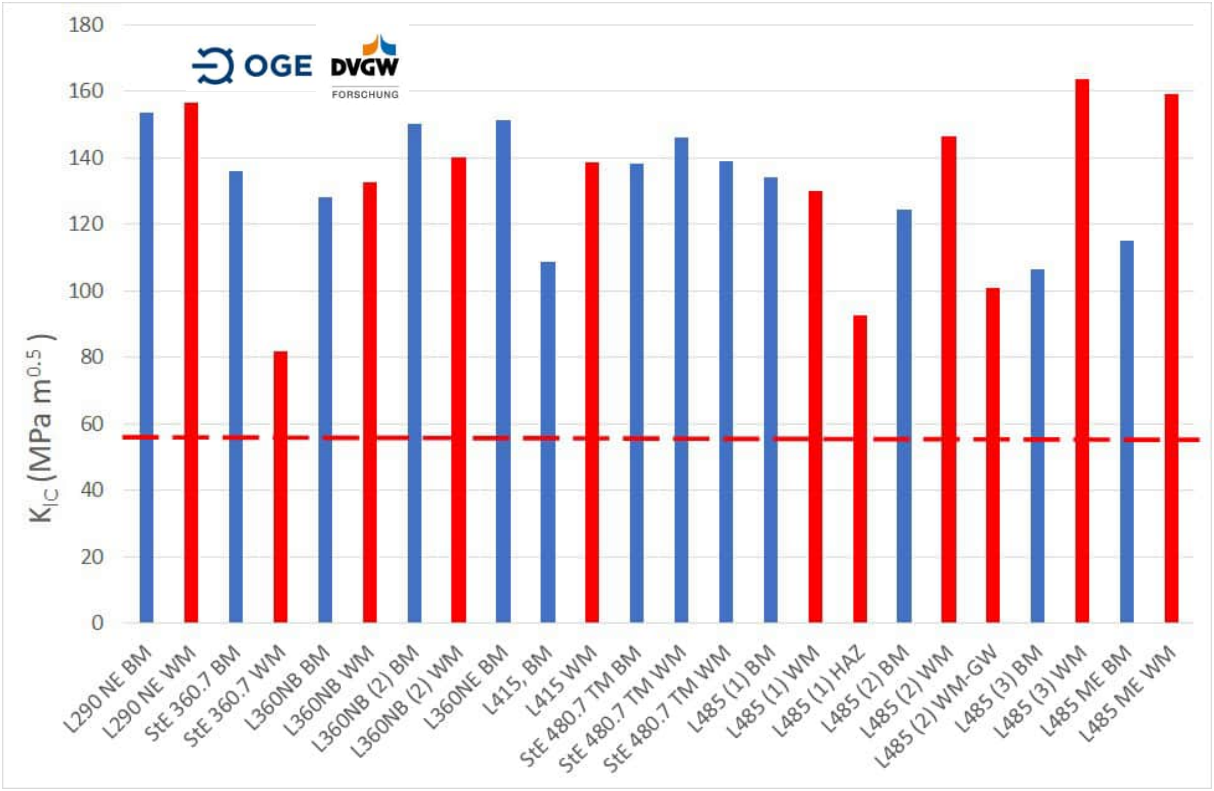

Figure 5.3: Established fracture toughness (K_{Ic}) for the tested pipeline materials (3)

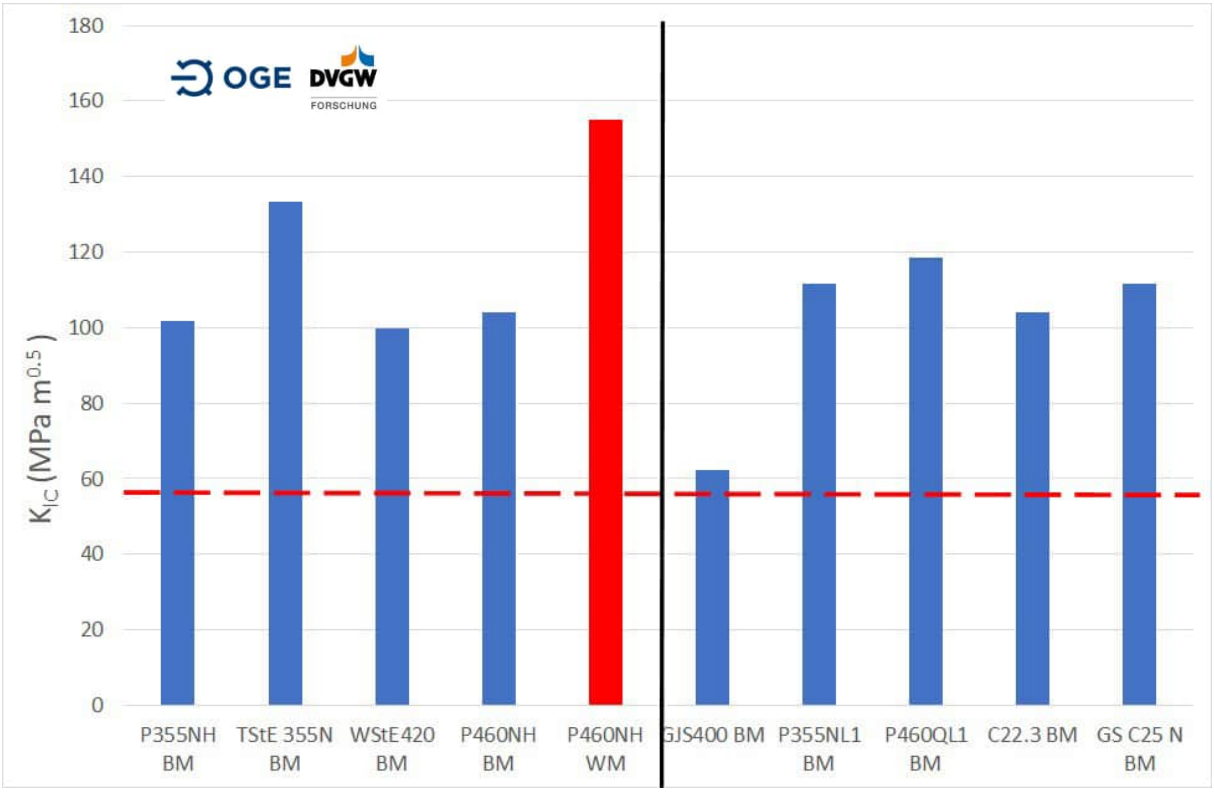

Figure 5.4: Established fracture toughness (K_{Ic}) for line pipe materials (plants) and valves (pressure vessels)

All investigated samples complied with the minimum requirement for fracture toughness $K_{Ic} \geq 55$ MPam^{½} as per ASME B 31.12.

5.2 Results for p_{H2} < 100 bar

For the material St35, the impact of hydrogen pressure on the resulting fracture toughness was investigated for two different production years (Figures 5.5 and 5.6). Hydrogen pressure was varied for the base material exclusively. The highest fracture toughness values ($K_{Ic} \cong$ 170 MPa m^{½}) were established in air (0 bar H_2). A reproducible reduction in fracture toughness was established already at a low hydrogen pressure of p_{H2} = 0.2 bar. It was decreased to fracture toughness values of around $K_{Ic} \cong$ 100 MPam^{½} at hydrogen pressures of p_{H2} = 10 – 20 bar. If hydrogen pressure is further increased, this fracture toughness remains approximately constant.

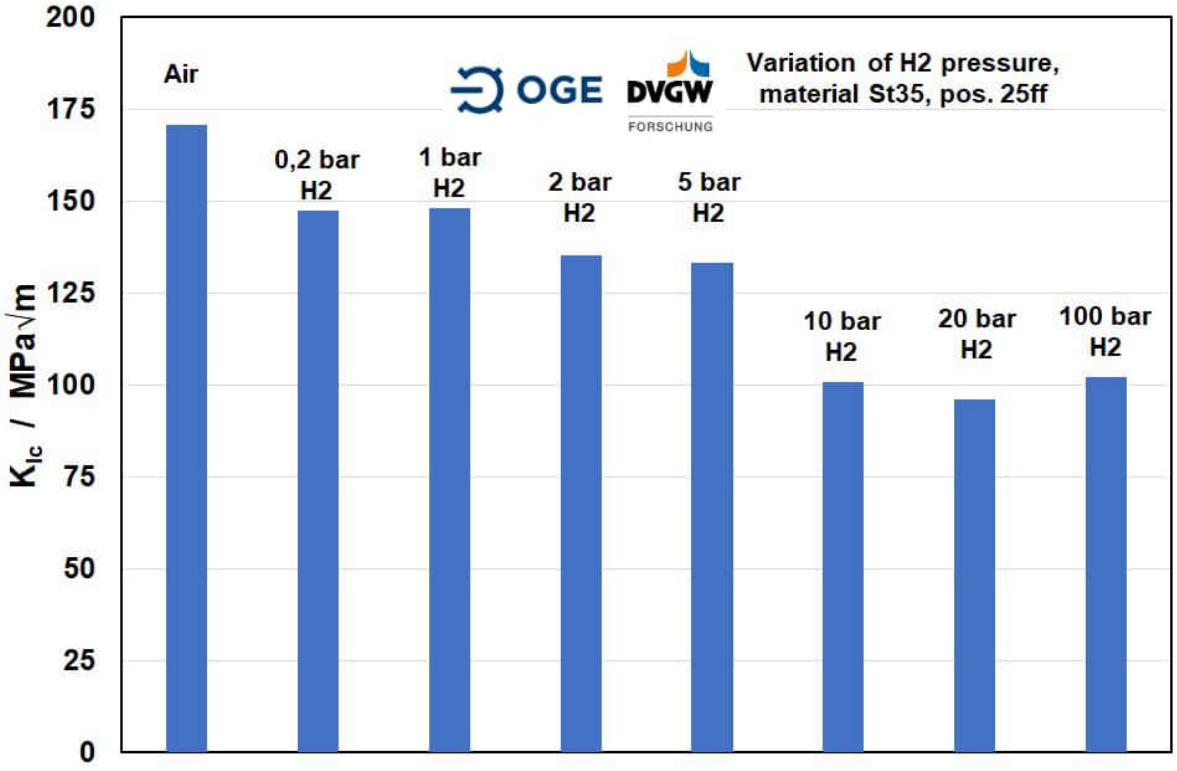

Figure 5.5: Fracture toughness depending on hydrogen pressure (St35, item no. 25ff)

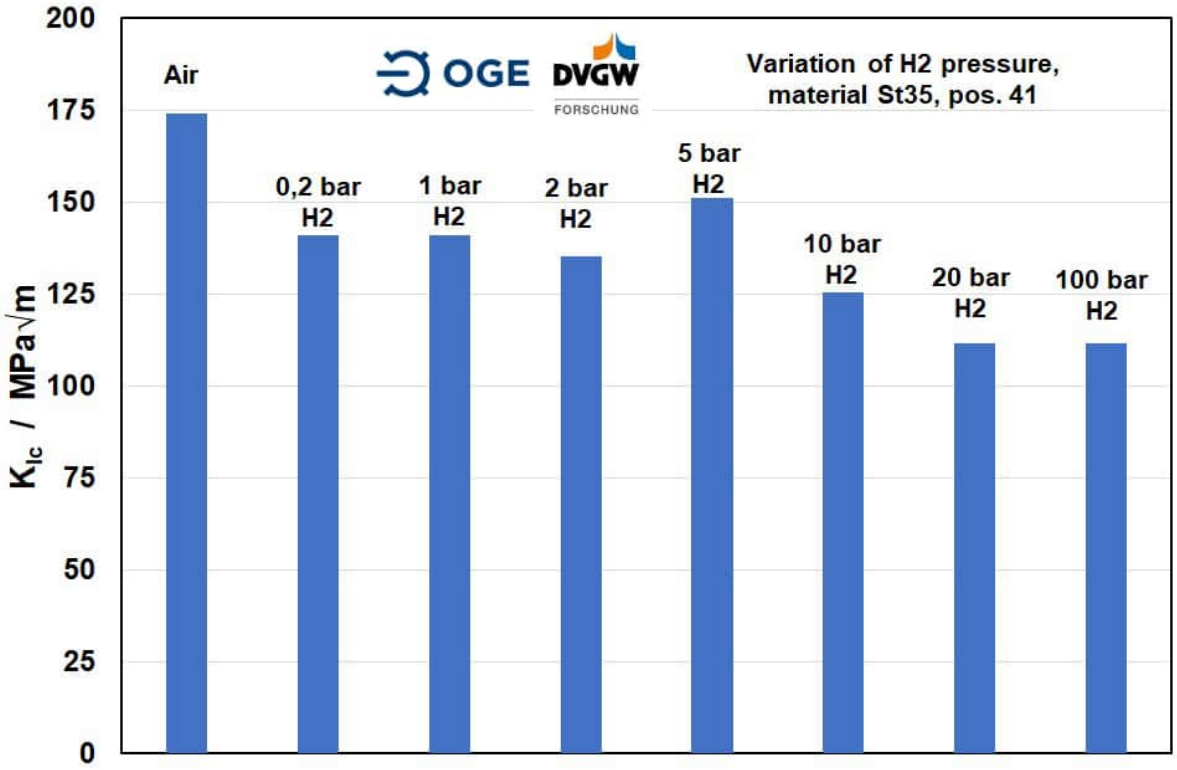

Figure 5.6: Fracture toughness depending on hydrogen pressure (St35, item no. 41)

For material L485 which is the currently used material, Figure 5.7 shows the dependence of fracture toughness on hydrogen pressure p_{H2}. The following results also refer to the base material only. In the case of this material, a distinct reduction in fracture toughness was established already at low hydrogen pressures. In this case, fracture toughness continuously decreases as hydrogen pressure p_{H2} increases. However, the stipulated minimum value of $K_{Ic} \geq 55$ Mpam$^{0.5}$ was always considerably exceeded.

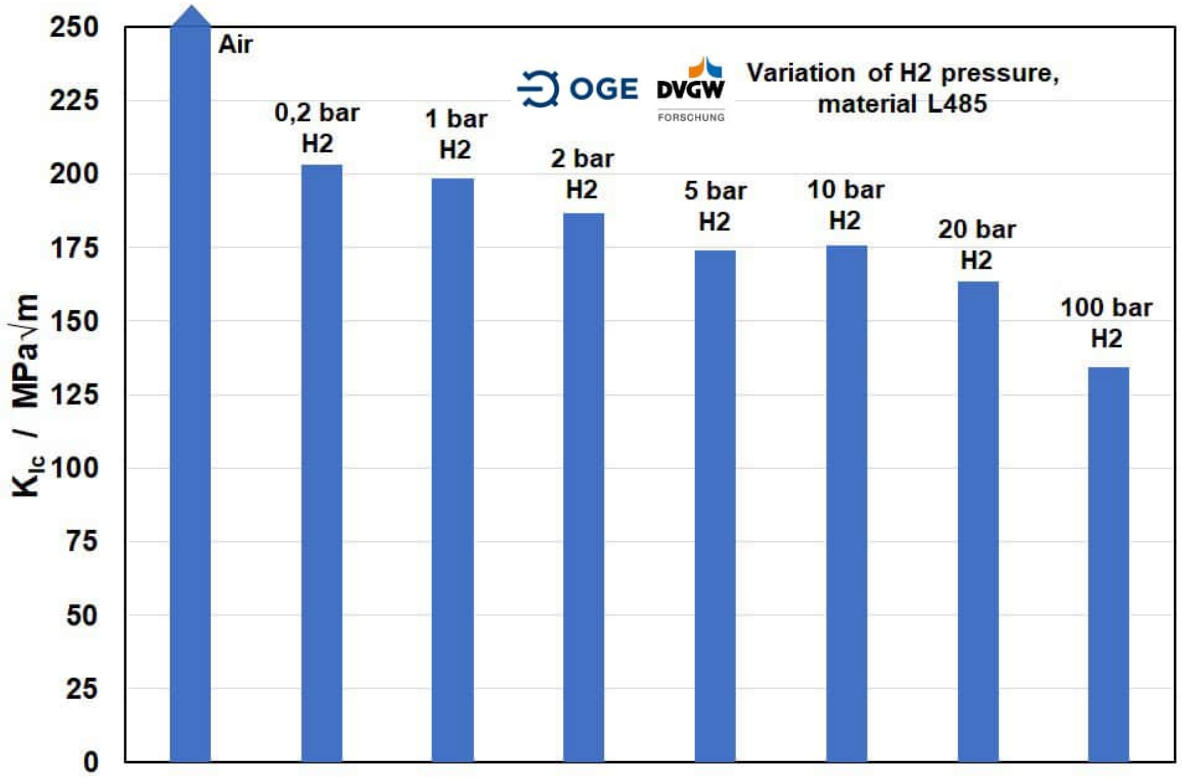

Figure 5.7: Fracture toughness depending on hydrogen pressure (L485)

6 Conclusions and Outlook

The primary objective of the SyWeSt H2 project was to investigate the applicability and transferability of the fracture-mechanical parameters specifically indicated in ASME B 31.12 for hydrogen as a transmission medium to the pipe materials featured in the German high-pressure gas pipeline grid.

For this purpose, fracture-mechanical crack growth investigations were performed on a representative selection of pipeline steel grades of very different ages and material strengths and the relevant results were compared with the crack growth relationships defined by ASME B 31.12. This comparison indicated that there is considerable concurrence, also in quantitative terms, between the crack growth relationships defined by ASME and the crack growth relationships established in this project.

Hence, all pipeline steel grades investigated in this project are fundamentally suitable for hydrogen transmission.

Considered in detail, in comparison to ASME B 31.12, crack growth as established in this project is somewhat greater for lower cyclical stress intensities and somewhat less for higher cyclical stress intensities.

In practical application within the context of service life predictions to be performed, the application of both crack growth equations ought to lead to very similar results. Compared to the ASME crack growth equations, the bilinear relationships as established here also include the impact of hydrogen pressure and the mean stress level (R value). This enables more precise service life predictions which then result in longer predicted operating periods if higher stress intensities are decisive or relatively low hydrogen or partial hydrogen pressures apply. The latter can be particularly the case in distribution grids or with the blending of hydrogen.

In addition to crack growth behaviour, the minimum value for fracture toughness as specified in ASME B 31.12 and the DVGW codes of practice was investigated. This value was also exceeded by all investigated pipeline steel grades, in the majority of cases even very considerably. This also demonstrates the fundamental suitability for hydrogen transmission.

In addition to the tests on pipeline steel grades, a number of orienting fracture-mechanical tests were performed on materials which are used as pressure vessels for valves. It was shown that, in the majority of cases, the relevant results obtained are comparable with those for pipeline steel grades. Hence, the application of fracture-mechanical concepts for valve materials is possible or recommendable. Since, however, the wide range of potentially usable materials is very great, the initiation of an additional test programme specifically for these materials is highly advisable.

The SyWeSt H2 project covers a large quantity of data, and further analyses / evaluations would also appear highly advisable. This particularly relates to questions to what extent, for example, the age, strength level, phosphorus and sulphur content or carbon equivalent influence the fracture-mechanical properties of the materials.

The impact of weld hardness on the resulting fracture-mechanical properties was only exemplarily investigated by the SyWeSt H2 project. However, indications resulted that the maximum hardness specified by ASME B 31.12 is very conservative, whereas the maximum possible hardness defined by the DVGW code of practice is too high with a view to potential

embrittlement due to hydrogen. Systematic additional investigations would have to be performed in order to viably define precise threshold values. The initiation of an appropriate test programme is currently being discussed at the European level.

The crack growth relationships derived from the SyWeSt H2 project include the impact of hydrogen or partial hydrogen pressure, although this was estimated very conservatively (i.e. “on the safe side”). In fact, however, no impact by hydrogen on crack growth behaviour for hydrogen pressures of p_{H2} ≤1 bar was established in the measurements performed. If this result can also be evidenced for further materials, this could have a very beneficial effect on the operation of gas grids with low pressure levels or additions of hydrogen in large-scale grids.

Fundamentally, a more precise description of the impact of average stress (R value) would be desirable. However, considering the existing complexity and the associated scope of research, the work on this topic is to be considered as very intensive.

7 Literature

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8 List of Abbreviations

BM	*Base material*
COD	*crack opening displacement*
DVGW	*Deutscher Verein der Gas- und Wasserwirtschaft (German Technical and Scientific Association for Gas and Water)*
ERW	*Electric Resistance Welding*
GW	*girth weld*
HAZ	*heat-affected zone*
LW	*longitudinal weld*
WM	*weld material*
WM-GW	*weld material of the girth weld*
WM-LW	*weld material of the longitudinal weld*

9 List of Symbols

R_e	Minimum yield strength	MPa
R_m	Minimum tensile strength	MPa
K_v	Notched-bar impact work	J
K_{JIc}	Fracture toughness calculated from J_{Ic} value	MPa$\sqrt{m}$
K_v /A	Notched-bar impact strength	kgm/cm^2
E	Young's modulus	MPa
μ	Poisson's ratio	-
K_{min}/K_{max}	R ratio	-
C ΔK^m	Paris equation	mm/load cycle
J	J integral	J/mm^2
A	Sample cross section	mm^2
Δa	Change in crack depth	mm
f	Test frequency	Hz
R	Mean stress ratio	-
ΔK	Cyclic stress intensity	MPa$\sqrt{m}$
ΔK_{th}	Lower threshold value for crack growth	MPa$\sqrt{m}$
p_{H2}	Hydrogen pressure	bar
da/dN	Crack depth growth per load cycle	mm/load cycle

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DVGW Deutscher Verein des
Gas- und Wasserfaches e. V.
Technisch-wissenschaftlicher Verein
Josef-Wirmer-Straße 1–3
53123 Bonn

Tel.: +49 228 9188-5
Fax: +49 228 9188-990
E-mail: info@dvgw.de
Internet: www.dvgw.de

Download as pdf under: www.dvgw.de

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