

Deutscher Verein des Gas- und Wasserfaches e.V.



www.h2-dvgw.de

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

Final Report

Januar 2023

DVGW Funding Code G 202006

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 crosssection 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.

Table of Contents

1	Ter	ms of Reference	3
2	Bas	sic Procedure for Performance of Fracture-Mechanical Tests	4
	2.1	Test Set-up for Performance of Fracture-Mechanical Tests in Hydrogen Atmosph	
	2.2	Cyclical Tests: Testing and Evaluation as per ASME E647 [5]	
	2.3	Static Fracture-Mechanical Testing: Testing and Evaluation as per ASTM E1820	9
3	Inv	estigated Materials	11
	3.1	L290 NE	14
	3.2	5L Grade A	
	3.3	St35	
	3.4	15k (St35)	
	3.5	X42	37
	3.6	RR St43.7	43
	3.7	P355 NH/NL2	45
	3.8	L360NE	47
	3.9	L360NB (Batch 2)	
	3.10	X46 / StE320.7	
	3.11	StE360.7	
	3.12	StE480.7 TM	
	3.13	L360 NB	
	3.14	14HGS	
	3.15	WSTE 420	
	3.16	St53.7	
	3.17	X56.7	
	3.18	St60.7	
	3.19	P460 NH	
	3.20	X70	
	3.21	L485	
		L485 ME	
	3.23 3.24	L485 (Batch 2) GRS550/X80	
	3.24	L415	
	3.26	P355 NL1	
	3.27	GJS400	
	3.28	P460 QL1	
	3.29	C22.3	
	3.30	GS C25 N	
	3.31	TStE 355N	
4		sults of Crack Growth Measurements	
	4.1	Crack Growth at p_{H2} = 100 bar and R=0.5	
	4.1	Crack Growth Law Depending on Hydrogen Pressure p_{H2}	
	4.2	Additional Consideration of Mean Stress (R Value)	
5		ected Results for Fracture Toughness	
J		COLOG I NOSULIS IVI I TAVIULE I VUYIIIESS	112

Ę	5.1	Results for p _{H2} = 100 bar	.172
Ę	5.2	Results for p _{H2} < 100 bar	.174
6	Cor	nclusions and Outlook	.177
7	Lite	rature	.179
8	List	of Abbreviations	.180
9	List	of Symbols	.181
10	List	of Figures	.182
11	List	of Tables	.186

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_{lc}) 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, fracturemechanical 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).

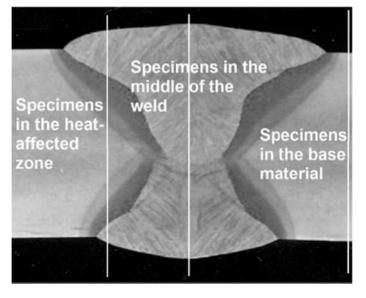


Figure 2.1: Cross-section of a submerged arc-welded steel pipe

Due to the different pipe geometries of gas transmission pipelines, the sample size for fracturemechanical 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).

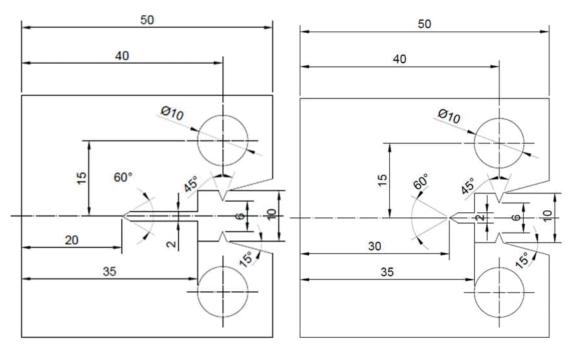


Figure 2.2: Sample geometry for static tests (left) and cyclical tests (right)

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.

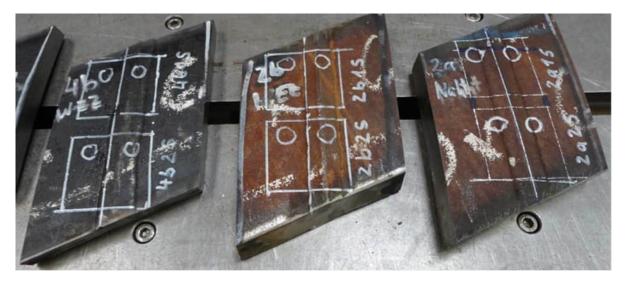


Figure 2.3: Removal of samples from a spiral welded pipe

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).

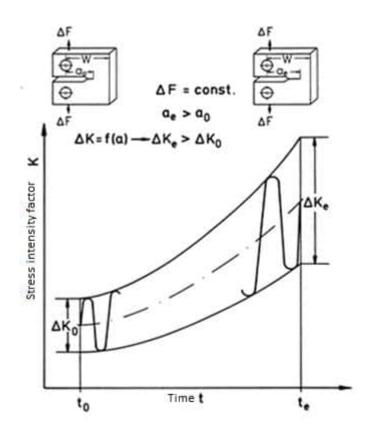


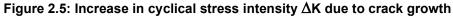
Figure 2.4: Servohydraulic testing system of MPA Stuttgart using an integrated hydrogen autoclave

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).





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).

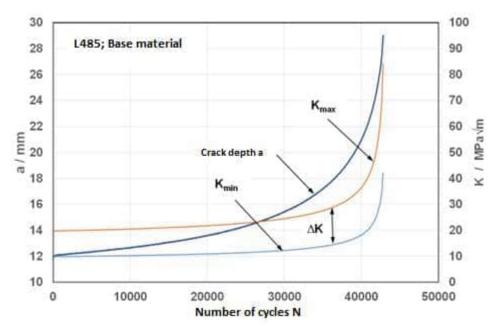


Figure 2.6: Crack depth and stress intensities K_{min} , K_{max} and $\Delta \bm{K}$ depending on the number of cycles during testing

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:

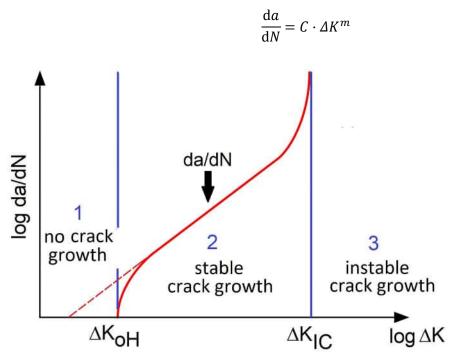


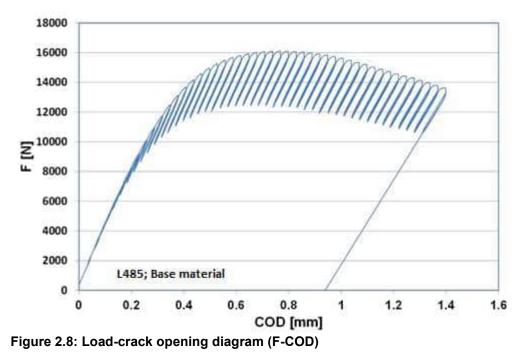
Figure 2.7: Schematic representation of crack growth depending on cyclical stress intensity $\Delta {\rm K}$

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).



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).

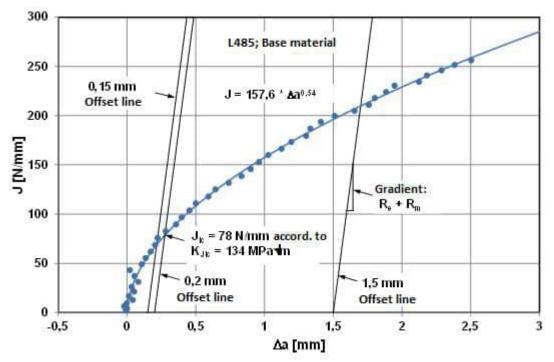


Figure 2.9: Crack resistance curve (JR curve)

Using this curve and the 0.2 mm offset line, the fracture-mechanical parameter J_{lc} is established as the point where the curve intersects with this offset line. This J_{lc} 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_{lc} value, the K_{Jlc} 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	Legend	
15 k (St.35)	BM, SAWL, GW	da/dN Crack growth	
X42	BM, ERW, GW, HAZ	K _{IC} Fracture toughness	
RR St 43.7	BM	BM Base material	
P355 NH	BM	HAZ Heat-affected zone	
L360 NE	BM	SAWL Submerged arc longitudinal weld	
StE 360.7	SAWL, BM	SAWH Submerged arc spiral weld	
L360 NB	SAWL BM	ERW Electric Resistance Weld	
14 HGS	BM, LW, GW	GW Girth weld	
TStE 355 N	BM	LW Longitudinal weld	
WSTE 420	BM	WM Weld material	
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	0/0.2/1/2/3/10/20/100	
L360 NB	BM, WM		
StE 320.7	BM, GW	10 / 100	
StE 480.7 TM	BM, SAWL, GW		
L485	BM	100	0.1 / 0.5 / 0.7
L360	BM	100	0.1/0.3/0./

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.

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

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 (201	8-09)	
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

Chamiest same sitism	С	Si	Mn	Ρ	S	Cu	Cr	Мо
Chemical composition [%]	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

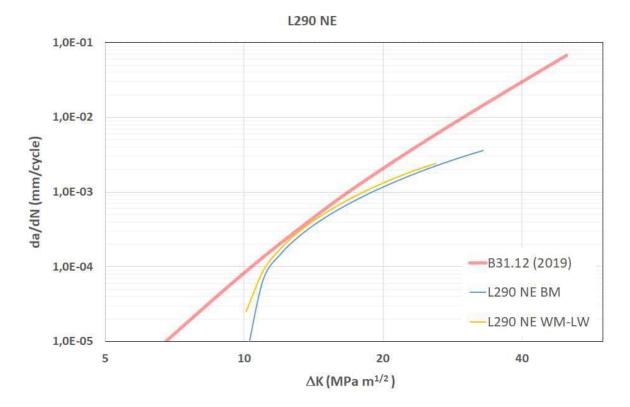


Figure 3.3: Crack growth L290 NE

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.

			MF	Test rep AS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample descr	iption	39.1; Outer	layer		15	Constantial States		
Administrato	r	Silcher			Same and the second			
Test instrum			1					
Serial numbe		Zwick Z 323	5357.00904					
		H2932-002-	50430					
Test conditio	ns							
HV ·	10	DIN EN ISO	6507-1:201	8-07			- Contraction	
HBW		DIN EN ISO	6506-1:201	5-02				
HRC		DIN EN ISO	6508-1:201	6-12				
	Test ten	peratur, if ou						
Control	280.6	280,8	0,281	235				
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	d _{in}	Hardness	Mean value	Distance in	Description	
No.	μm	μm	mm	HV	HV	mm	Remark	
	247.0	244.5	0.2400	100				
1	317,6 316,3	314,5 316,1	0,3160 0,3162	186 185	181		-	
3	318,8	317,0	0,3102	184			BM 1	
4	321,7	323,0	0,3223	178			DIVII	
5	328,8	328,4	0,3286	172			-	
1	320,3	320,9	0,3206	180				
2	315,3	314,2	0,3148	187				
3	311,6	310,3	0,3109	192	188		HAZ 1	
4	313,0	308,0	0,3105	192	, I I I I I I I I I I I I I I I I I I I		Station and State	
5	316,5	313,2	0,3149	187			<u></u>	
1	292,0	291,8	0,2919	218			-	
2	304,1 310,1	303,5 308,4	0,3038	201 194	202			
4	306,4	308,4	0,3093	194	202		WM	
5	302,0	307,0	0,3028	202	1		1	
1	304,5	304,3	0,3044	200				
2	301,2	303,5	0,3023	203	1		1	
3	312,2	312,2	0,3122	190	193		HAZ 2	
4	315,5	316,3	0,3159	186			1000000000000	
5	315,3	315,3	0,3153	187				
1	331,3	331,9	0,3316	169			4	
2	326,1	325,5	0,3258 0,3232	175 178	176			
3	322,6 321,9	323,8 324,0	0,3232	178	176		BM 2	
5	320,7	319,0	0,3230	181				
Date:	06.11.22							
Tester	School							
Tester:	Scheck							

Figure 3.4: Hardness measurements of L290 NE (1)

			MF	Test re PAS-PPB 523 Hardnes	310-08/1	Metallog	erat raphie und mikroskopie
Order numb	er	9039784000)				
Sample desc	ription	39.1; Cente	er			M TANK	
Administrat	or	Silcher					
Test instrum	22		(====)				
		Zwick Z 323		2	•		
Serial number	er	H2932-002-	50430				
Test conditio	ins						
U HV	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC	6506-1.201	5-02			
C. HORAS			2.702.01000				
HRC	- Chevroline - Chevroline	DIN EN ISC					
	Concession (Decord	peratur, if ou	and sector strength strength				
Control	280,6	280,8	0,281	235		Reference: 2	37 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	dz	d _m	Hardness HV	Mean value HV	Distance in	Remark
no,	μm	μm	mm	nv	nv	mm	200000000000000000000000000000000000000
1	324,8	326,5	0,3257	175			
2	325,9	326,7	0,3263	174			
3	326,9	326,3	0,3266	174	174		BM 1
4	324,4	327,3	0,3259	175			
5	325,7 321,1	329,6	0,3276	173 176			
1	321,1	327,9 317,6	0,3245 0,3193	176	4		
3	320,3	319,4	0,3199	181	179		HAZ 1
4	320,5	320,9	0,3207	180			
5	323,6	322,8	0,3232	178	1		
1	316,1	316,9	0,3165	185			
2	320,3	319,7	0,3200	181			
3	318,8	319,9	0,3193	182	181		BM
4	323,4 325,0	321,5	0,3224 0,3237	178 177	4		
5	325,0	322,3 326,3	0,3237	177			
2	330,0	330,0	0,3201	170	1		
3	321,9	321,5	0,3217	179	175		HAZ 2
4	324,2	323,4	0,3238	177			
5	325,5	325,5	0,3255	175			
1	340,6	339,6	0,3401	160	4 1		
2	339,8	342,9	0,3413	159	100		
3 4	332,5 328,4	334,6 329,4	0,3336 0,3289	167 171	166		BM 2
5	328,4	329,4	0,3289	171	1		
	06.11.22 Scheck						

Figure 3.5: Hardness measurements of L290 NE (2)

			MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat ographie und enmikroskopie
Order numb	ber	9039784000)				
Sample desc	ription	39.1; Root	6				
Administrat		Silcher					
Test instrum	nent	Zwick Z 323	(neu)				
Serial numb	er	H2932-002-	50430				
Test conditio	ons						
			0507 4 004	• • •			
U HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if out					
Control	280,6	280,8	0,281	235		56949	Descenario - No.
plate	280,0 µm	μm	0,201 mm	HV		Reference:	237 HV 10
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	
no.	μm	μm	mm	HV	HV	mm	Remark
1.2		Part					
1	323,8	329,8	0,3268	174			
2	336,3	337,7	0,3370	163] [
3	335,2 334,6	335,8 333,3	0,3355 0,3340	165 166	165		BM 1
4	341,6	341,0	0,3340	159			1
1	332,5	333,3	0,3329	167			
2	324,0	324,4	0,3242	176]
3	328,0	326,5	0,3272	173	173		HAZ 1
4	329,4	330,6	0,3300	170			
5	324,6 322,6	321,5 323,6	0,3231 0,3231	178 178			
2	324,4	325,2	0,3248	176			1
3	328,4	324,8	0,3266	174	175		WM
4	326,7	326,3	0,3265	174]
5	326,9	324,0	0,3255	175			
1	336,0 329,6	332,7 336,5	0,3344 0,3330	166 167			4
3	329,0	330,5	0,3330	166	165		HAZ 2
4	333,1	333,3	0,3332	167			
5	342,5	343,1	0,3428	158			
1	341,9	343,7	0,3428	158			
2	340,6	340,6	0,3406	160	160		
3	338,7 337,9	338,9 339,0	0,3388 0,3384	162 162	162		. BM 2
5	329,6	333,3	0,3315	169		-	1
	,-						
	06.11.22 Scheck						

Figure 3.6: Hardness measurements of L290 NE (3)

			Test reportReferatMPAS-PPB 52310-08/1Metallographie undHardness testElektronenmikroskopie				
Order numb	er	9039784000	1				
Sample desc	ription	39.2; Outer	layer				
Administrate		Silcher					
		- 1890-1843-194 	(
Test instrum		Zwick Z 323	AB BA				
Serial number	er	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW	5-510	DIN EN ISO	6506-1.201	5-02			
1100 1000 2000							
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if out	side (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		Herefeller	237 HV 10
Indentation	d,	d₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	
1	315,5	316,3	0,3159	186			
2	314,0	315,1	0,3139	180	1 1		
3	314,0	315,1	0,3146	187	186		BM 1
4	315,7	317,4	0,3165	185	1 ¹⁰⁰ F		
5	319,2	318,4	0,3188	182			
1	306,8	309,7	0,3082	195			
2	305,1	305,7	0,3054	199		-	
3	311,1	312,4	0,3118	191	194		HAZ 1
4	312,2	311,8	0,3120	191			
5	310,9 299,9	310,5 301,4	0,3107	192 205	***********	************	
2	305,5	303,9	0,3007	205			
3	309,1	306,6	0,3047	196	199		WМ
4	305,3	307,4	0.3064	198			
5	309,5	306,2	0,3078	196			
1	316,3	317,6	0,3170	185			
2	316,3	315,1	0,3157	186			
3	313,6	314,0	0,3138	188	188	-	HAZ 2
4	312,4	313,6	0,3130	189			
5	312,4	309,9	0,3111	192			
1	336,1	335,8	0,3359	164			
2	329,6 326,5	328,8 324,4	0,3292 0,3255	171 175	175		
4	328,5	324,4	0,3235	175	175		BM 2
5	315,9	315,7	0,3158	186			
Date:	06.11.22						
Tester:	Scheck						

Figure 3.7: Hardness measurements of L290 NE (4)

			MP	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	39.2; Cente	er				
Administrate	or	Silcher					
Test instrum	22		()				
		Zwick Z 323					
Serial number	er	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1.201	5_02			
110 MGR 2200							
HRC		DIN EN ISO					
	A CHORNEL DATE OF	peratur, if out	side (23+/-	5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	survey and the
1	321,5	325,0	0,3233	177			
2	321,7	324,0	0,3229	178	176]
3	327,3	324,2	0,3258	175			BM 1
4	322,8	323,4	0,3231	178 174			
5	325,9 318,8	327,1 321,7	0,3265	174			
2	319,9	319,9	0,3199	181			
3	321,3	320,9	0,3211	180	179		HAZ 1
4	323,0	319,4	0,3212	180			
5	324,6	326,9	0,3258	175			
1	316,5	315,1	0,3158	186 185			
2	318,4 317,2	315,3 316,1	0,3169 0,3166	185	183		WM
4	322,3	321,5	0,3219	179	100		V V I V I
5	322,8	320,1	0,3214	180			1
1	320,7	320,7	0,3207	180			
2	320,9	319,0	0,3200	181	100		
3	321,3 319,4	323,6 319,9	0,3224 0,3196	178 181	180		HAZ 2
5	320,3	319,9	0,3190	181	1		1
1	341,0	341,2	0,3411	159			
2	330,2	332,9	0,3316	169]
3	326,1	324,8	0,3255	175	172		BM 2
4	321,7 322,5	322,8 325,5	0,3222 0,3240	179 177			4
J	522,5	525,5	0,0240				
	06.11.22 Scheck						

Figure 3.8: Hardness measurements of L290 NE (5)

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000					
Sample desc	ription	39.2; Root					
Contractions - Marcola	urzeowestin.	Silcher					
Administrate	22 ₁₁₁						
Test instrum	ent	Zwick Z 323	(neu)				
Serial number	er	H2932-002-	50430				
Test conditio	ns						
		DIN EN ISO	6507 1:201	0.07			
22221 10.6.20	10			2014-2019			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou	tside (23+/-	5) °C			
Control	280,6	280.8	0,281	235			Lange and the
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Based
no.	μm	μm	mm	HV	HV	mm	Remark
1	334,2	335,0	0,3346	166			
2	336,9	338,9	0,3379	162	163		
3	331,5 340,6	334,4 341,0	0,3329	167 160			BM 1
5	340,2	340,2	0,3402	160			
1	335,2	333,8	0,3345	166			
2	331,3	329,4	0,3303	170			
3	331,9	331,3	0,3316	169	171		HAZ 1
4	327,5	327,5 323,4	0,3275	173 176			
5	326,1 328,0	323,4	0,3247	176			
2	327,8	327,9	0,3278	173			
3	329,8	326,1	0,3279	172	174		WM
4	325,7	324,4	0,3250	176			
5	325,3	323,8	0,3245	176			
1	323,2 323,6	321,7 323,4	0,3224 0,3235	178 177			
3	325,5	323,4	0,3255	174	176		HAZ 2
4	327,1	329,0	0,3281	172			
5	324,0	324,6	0,3243	176			
1	339,6	338,5	0,3391	161			
2	337,7	336,7	0,3372	163	166		
3	331,9 333,3	330,9 334,2	0,3314 0,3338	169 166	100		BM 2
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

Ob anni a la anna a iti an	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

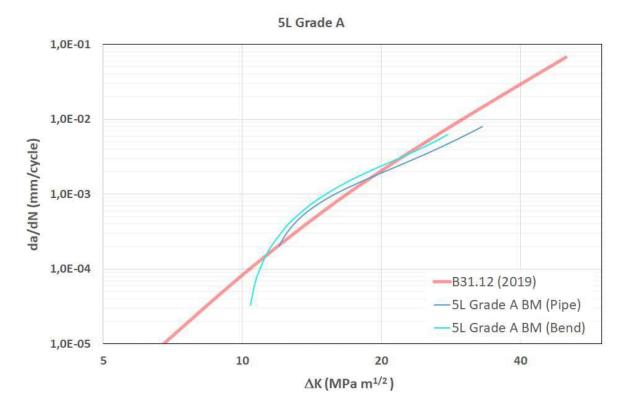


Figure 3.10: Crack growth 5L Grade A

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

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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

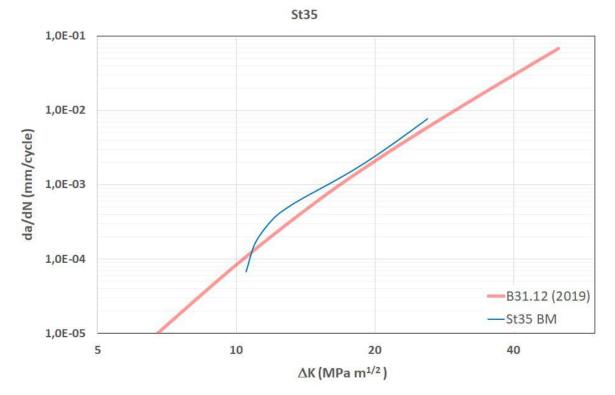


Figure 3.11: Crack growth St35

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.

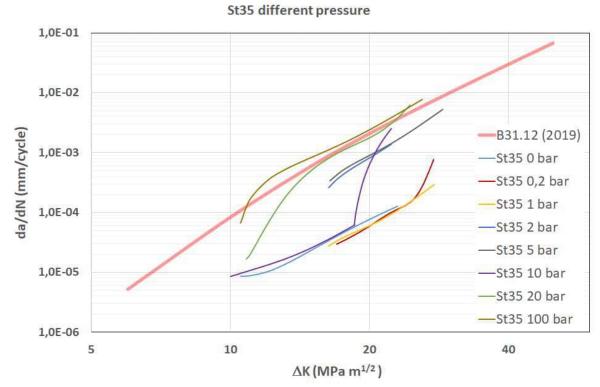


Figure 3.12: Crack growth St35 at different pressures

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

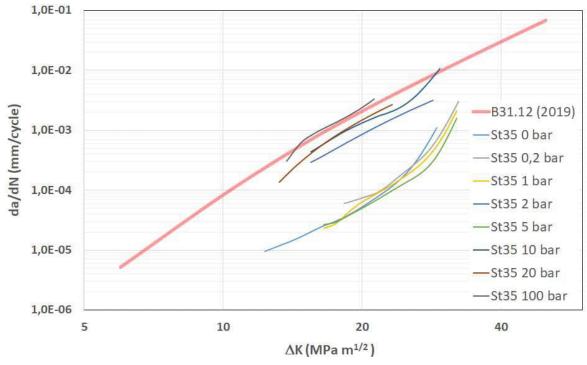
Table 3.11: Chemical composition of St35

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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.



St35 (Pos. 41) different pressure

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	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)

Chamical commonitien	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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

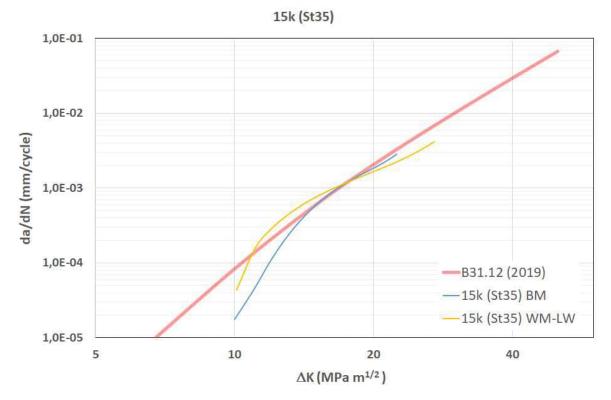


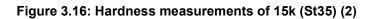
Figure 3.14: Crack growth 15k (St35)

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.

\mathbb{N}	STUTTGA	ART	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)					
Sample description		23A5S-1 Outer layer		1				
Administrator		Silcher						
		Zwick Z 323 (neu)						
Test instrument Serial number								
		H2932-002-50430						
Test conditio	ns							
J HV	10	DIN EN ISC	6507-1:201	8-07				
	5-51C	DIN EN ISO	6506-1.201	5-02				
HBW		DIN EN ISO 6506-1:2015-02						
HRC		DIN EN ISC	6508-1:201	6-12				
	Test temp	peratur, if ou	tside (23+/-	5) *C				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
plate	μm	μm	mm	HV			257 114 10	
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark	
10.	μm	μm	mm	HV	HV	mm	2010/02/02/02	
1	254.2	359,1	0,3567	146				
2	354,3 360,5	361,2	0,3567	140			BM 1	
3	355,3	358,2	0,3568	146	142			
4	363,7	368,2	0,3659	138				
5	362,8	367,0	0,3649	139				
1	358,5	357,8	0,3581	145			HAZ 1	
2	358,0	354,7	0,3564	146	147			
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	343,9 340,8	343,5 338,6	0,3437 0,3397	157 161	155		WM	
2	340,8	348,3	0,3397	154		-		
4	356,0	348,3	0,3474	134				
5	345,6	341,9	0,3437	157				
1	355,3	362,6	0,3590	144				
2	344,5	349,3	0,3469	154	149		HAZ 2	
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	363,7 365,3	367,6 370,5	0,3656 0,3679	139 137				
Date:	06.11.22							
Terter	Cabaala							
Tester:	Scheck							

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

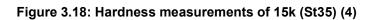
\mathbb{N}	STUTTGA	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000	(
Sample desc	ription	23A5S-2 0	ter layer				
Administrate	ar.	Silcher					
	22 _{- 42}						
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430		Real Property in		
Test conditio	ns						
J HV ·	10	DIN EN ISO	6507-1.201	8-07			
HBW		DIN EN ISO					
HRC		DIN EN ISO	6508-1:201	6-12			
	Test temp	peratur, if out	side (23+/-	5) *C			
Control	280,6	280,8	0,281	235		References	237 HV 10
plate	μm	μm	mm	HV		Neierence.	237 HV 10
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Kelliork
				450			
1	347,7 352,3	355,8 353,1	0,3517 0,3527	150 149			
3	352,5	354,3	0,3527	149	148		BM 1
4	356,4	359,5	0,3579	145	148		
5	350,6	353,9	0,3522	149			
1	362,2	363,9	0,3630	141			17
2	353,9	355,4	0,3546	147	1000		
3	355,1	357,2	0,3562	146	146		HAZ 1
4	354,1 353,7	353,3 354,9	0,3537 0,3543	148 148			
5	352,6	348,9	0,3543	140			-
2	352,0	346,0	0,3490	152		-	
3	352,4	351,6	0,3520	150	151		WM
4	354,7	353,3	0,3540	148			
5	350,2	347,0	0,3486	153			
1	367,2	369,3	0,3682	137			
2	352,4 353,9	350,4 352,4	0,3514 0,3532	150 149	147		HAZ 2
4	353,5	350,8	0,3532	149	147		
5	352,9	352,4	0,3527	149			
1	360,9	359,7	0,3603	143			
2	353,7	359,7	0,3567	146			
3	349,3	352,7	0,3510	151	147		BM 2
4	351,0 351,8	353,1 356,6	0,3520 0,3542	150 148			
5	551,0	000,0	0,0042	140			
Date:	06.11.22						<u>.</u> "
Tester:	Scheck						



\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und mmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	23A5S-2	Root				
Administrate	1175000765010	Silcher					
						CALIFORNIA CONTRACT	
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISC	6507-1:201	8-07			
		COMPANY NO.					
HBW			6506-1:201				
HRC		DIN EN ISC	6508-1:201	6-12			
	Test temp	peratur, if ou	tside (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		Hereice.	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
10.	μm	μm	mm	HV	HV	mm	104350805566
1	359,5	365,1	0,3623	141			-
2	362,6	369,9	0,3663	138			
3	357,6	362,0	0,3598	143	144		BM 1
4	361,4	364,7	0,3630	141		-	
5	340,0	348,1	0,3440	157			
1	374,7	363,2	0,3689	136			
2	353,7	351,0	0,3523	149	140		
3	352,9 353,7	351,4 352,4	0,3521 0,3531	150 149	146		HAZ 1
5	356,0	353,5	0,3547	149	1		
1	343,9	340,6	0,3423	158			
2	342.1	344,3	0,3432	157	1 1		
3	336,9	335,8	0,3364	164	159		WM
4	337,9	338,7	0,3383	162			
5	348,3	347,9	0,3481	153			
1	356,0	355,5	0,3558	147			
2	353,7	352,0	0,3529	149	140		
3	353,9	353,5	0,3537 0,3515	148 150	148		HAZ 2
4	351,8 356,6	351,2 357,6	0,3515	145	1 1	-	
1	364,7	365,9	0,3653	139			-
2	356,2	359,5	0,3578	145	1		
3	356,8	367,6	0,3622	141	142		BM 2
4	359,5	361,4	0,3604	143			
5	358,7	363,2	0,3610	142			
Deter						*******	
Date:	06.11.22						
Tester:	Scheck						
- concert	Geneen						

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

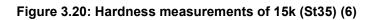
\mathbb{N}	STUTTG		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	23C.1; Out	er layer				State of the second
Administrate	1112200-0122010	Silcher	Second and a second			"我们有关"	
Test instrum		Zwick Z 323	(neu)			• •	
Serial numbe	er	H2932-002-	50430				
Test conditio	ns						
⊡н∨ ∙	10	DIN EN ISC	6507-1:201	8-07			
HBW	5-51C	DIN EN ISC		- 1-0.100319			
A Carlos and							
HRC		DIN EN ISC					
	A CHORD IN CONTRACTOR	peratur, if out	CONSCIPTION CONSTR	1. 1. 1. O.S			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	EDITOCOMOTONIO
1	355,8	362,8	0,3593	144			-
2	355,3	361,4	0,3584	144			
3	348,7	355,6	0,3521	150	145		BM 1
4	352,7	360,7	0,3567	146			
5	357,6	364,7	0,3612	142			
1	347,3	353,5	0,3504	151			
2	341,6	343,1	0,3424	158 158	156		
3	341,2 341,6	345,0 345,4	0,3431 0,3435	156	150		HAZ 1
5	342,9	346,6	0,3433	156			
1	331,9	328,0	0,3299	170			
2	325,0	328,8	0,3269	174			
3	325,9	330,0	0,3280	172	175		WM
4	327,3	316,7	0,3220	179]
5	322,5	322,3	0,3224	178			
1	347,7	353,3	0,3505	151	.		
2	344,3 351,2	350,8	0,3476	154 153	153		
4	347,9	344,8 350,0	0,3480 0,3489	153	155		HAZ 2
5	344,6	347,0	0,3458	155	1		
1	359,7	361,4	0,3605	143			
2	353,7	357,0	0,3553	147]		
3	352,9	359,9	0,3564	146	147		BM 2
4	352,2	354,7	0,3535	148	4		
5	352,7	354,9	0,3538	148			
Date:	06.11.22	1					I
Tester:	Scheck						



Order number 9039784000 Sample description 23C.1; Root Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HW DIN EN ISO 6508-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/5) °C Reference: 237 HV 10 Indentation d- d- HW Distance in mm 1 344,8 349,8 0,3473 154 149 2 343,3 346,0 0,3612 142 149 BM 1 1 344,8 349,8 0,3612 142 149 HAZ 1 2 357,6 360,7 0,3592 144 149 HAZ 1 2 342,5 349,8 0,3315 155 154 HAZ 1 2 357,6 363,0 0,3315 166 149 144 142 144	\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HW DI DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outsile (23+/5) °C Control 206, 208, 0,281 235 Plate µm µm HV Distance in Remar Indentation d1 d4, d2, d_m Hardness Mean value Distance in Remar I 344,8 349,8 0,3473 154	Order numb	ber	9039784000)				
Test instrument Zwick Z 323 (neu) Serial number H 2932-002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6506-1:2016-12 Test temperatur, if outside (23+/-5) °C Control 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation d1 d2 d4 HV Distance in mm ym ym mm HV Distance in mm Remar 1 344,8 349,8 0,3473 154	Sample desc	ription	23C.1; Roo	t		Take P		and some man
Test instrument Zwick Z 323 (neu) Serial number H2932002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HW 10 DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outsile (23+/5) °C Control 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation d1 d2 dm Hardness Mean value Distance in mm Remar 1 344,8 349,8 0,3473 154	Administrat	or	Silcher					
Serial number H2932-002-50430 Test conditions H2932-002-50430 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 280,6 280,6 237 HV 10 Indentation d, d, d, d, 237 HV 10 Indentation d, d, d, Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">Colspan="2">D, D, D, D, D, D, D, Colspan="2">Colspan="2"		22 ₁₀						
Test conditions HV 10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/5) °C Control 280,6 280,8 0,281 235 Control 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation d, d, d, d, Hr Mm HV Reference: 237 HV 10 Indentation d, d, d, d, Hr mm HV Mm Remar 1 344,8 349,8 0,3473 154 mm			ZWICK Z 323	(neu)				
HV 10 DIN EN ISO 6507-1:2018-07 DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) *C Reference: 237 HV 10 Indentation no. 41 42 4m Hardness Mean value Distance in mm Remar 1 344,8 349,8 0,3473 154 Mean value Distance in mm Remar 1 344,8 349,8 0,3473 154 Remar mm HV Mean value Distance in mm Remar 1 344,8 349,8 0,3473 154 Remar	Serial numb	er	H2932-002-	50430				
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 µm µm Reference: 237 HV 10 Indentation no. d₁ d₂ d₄m Hardness Mean value Distance in mm Remar 1 344.8 349.8 0.3473 154. HV Distance in mm Remar 1 344.8 349.8 0.3473 154. HV Distance in mm Remar 1 344.8 349.8 0.3473 154. HPV Mean value Distance in mm Remar 1 344.9 357.6 0.3533 149 H9 HBM 1 4 357.4 364.9 0.3612 142 HA HA 1 349.9 350.2 0.3501 151 HAZ HAZ HAZ 2 352.6 349.8 0.3411 157 HAZ HAZ HAZ HAZ HAZ HAZ	Test conditio	ons						
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 μm μm Reference: 237 HV 10 Indentation no. d1 d2 d4m Hardness Mean value Distance in mm Remark 1 344.8 349.8 0.3473 154. HV Distance in mm Remark 1 344.8 349.8 0.3473 154. HV Distance in mm Remark 1 344.8 349.8 0.3473 154. HV Distance in mm Remark 1 344.8 349.8 0.3473 154. HV Mean value Distance in mm Remark 2 357.6 0.3532 149 H9 BM 1 HAZ 1 349.9 350.2 0.3501 151 HAZ	U HV	10	DIN EN ISC	6507-1:201	8-07			
$\begin{tabular}{ c c c c c } \hline Test temperatur, if outside (23+/-5) *C \\ \hline Control plate μm$ μm$ μm$ mm$ HV $$Reference: $237 HV 10$ \\ \hline Indentation no$, μm$ μm$ mm$ HV $$Mean value HV $$Distance in mm$ mm$ mm$ HV $$Mean value HV $$Distance in mm$ mm$ mm$ HV $$HV$ $$Distance in mm$ mm$ mm$ HV $$HV$ $$Distance in mm$ mm$ mm$ $$HV$ $$HV$ $$HV$ $$Distance in mm$ mm$ $$mm $$HV$ $$HV$ $$HV$ $$Distance in mm$ mm$ $$mm $$HV$ $$HV$ $$HV$ $$Mean value HV $$HV$ $$mm $$mm $$HV$ $$HV$ $$HV$ $$Distance in mm$ $$mm $$mm $$HV$ $$HV$ $$HV$ $$HV$ $$HV$ $$hmm$ $$mm $$mm $$mm $$mm $$mm $$HV$ $$HV$ $$HV$ $$HV$ $$hmm$ $$mm $$mm $$mm $$mm $$hhhh	HBW		DIN EN ISC	6506-1:201	5-02			
$ \begin{array}{ c c c c c c } \hline \begin{tabular}{ c c c c } \hline \begin{tabual}{ c c } \hline \hline \begin{tabual}{ c c } \hline \hline \begin{tabual}{ c c } \hline \begin{tabual}{ c c } \hline \hline \begin{tabual}{ c c } \hline \hline \begin{tabual}{ c c } \hline \hline \begin{tabual}{ c c c c } \hline \hline \begin{tabual}{ c c c c } \hline \hline \begin{tabual}{ c c c c } \hline \hline \begin{tabual}{ c c c c } \hline \hline \begin{tabual}{ c c c } \hline \hline \begin{tabual}{ c c c } \hline \hline \begin{tabual}{ c$	The street see		. 2003 AR 503-00	12.000.00 0.0000000	172 - 5781780 -		3	3°
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$								
$ \begin{array}{ c c c c c c c } \hline plate & \mum & \mum & mm & HV & \begin{tabular}{ c c c c c c c } \hline plate & \mum & \mum & mm & HV & Mean value & Distance in & $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$								
$\begin{array}{ c c c c c c c } \hline plate & \mum & \mum & mm & HV \\ \hline Indentation & d_1 & d_2 & d_m & Hardness & Mean value & Distance in mm & HV & HV & mm & mm & HV & HV & mm & mm$							Reference:	237 HV 10
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$						1010	ST TANDAUM AND TANK OF	
1 344,8 349,8 0,3473 154 2 343,3 346,0 0,3447 156 3 348,9 357,6 0,3533 149 149 BM 1 4 357,4 364,9 0,3612 142 149 HAZ 149 BM 1 5 357,6 360,7 0,3592 144 149 HAZ 149 HAZ 1349,9 350,2 0,3501 151 150 150 151 150 154 HAZ 1 HAZ 1 153 154 HAZ 1 143 143 149 142 154 154 154 154 154 154 154 154 154 154 154 154 154 154 155 153 154 154 154 154 155 155 155 155 155 155 155 155 155 155 155 155 155 165 153 155 155 155	THE PROPERTY OF TACKING	S545	2014/03/06/201	5452,020		11.2 CONTRACTOR STOCKS 5 CONT	The second state of the second se	Remark
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	no,	μm	μm	mm	HV	HV	mm	201000000000
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	a 4	344.8	340.8	0 3473	154		1	
3 348,9 357,6 0,3533 149 149 BM 1 4 357,4 364,9 0,3612 142 142 142 142 144 <t< td=""><td></td><td></td><td></td><td></td><td>1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1</td><td></td><td></td><td></td></t<>					1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1			
4 357,4 364,9 0,3612 142 5 357,6 360,7 0,3592 144 1 349,9 350,2 0,3501 151 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 0,3411 157 1 332,3 330,6 0,3315 169 2 333,3 34,8 0,3341 166 3 389,9 336,3 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 2 353,1 352,0 0,3525 149 3 341,1 340,8 0,3410 160 5 342,3 343,7 0,3422						149		BM 1
1 349,9 350,2 0,3501 151 2 352,6 349,8 0,3512 150 3 343,5 349,1 0,3463 155 154 4 341,0 343,1 0,3420 158 154 HAZ 1 5 344,4 343,8 0,3411 157 154 HAZ 1 2 333,3 336,6 0,3315 169 4		357,4						
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 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 2 353,1 352,0 0,3525 149 3 341,1 340,8 0,3410 160 157 3 341,1 340,8 0,3420 158 157 HAZ 2 4 340,8 339,5 0,3402 160 157 HAZ 2 4 363,9 371,5 0,3677 137 <t< td=""><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></t<>	5							
3 343,5 349,1 0,3463 155 154 HAZ 1 4 341,0 343,1 0,3420 158 157 158 151 151 HAZ 1 1 332,3 330,6 0,3315 169 169 166 157 157 157 1								
4 341,0 343,1 0,3420 158 5 344,4 343,8 0,3441 157 1 332,3 330,6 0,3315 169 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 2 353,1 352,0 0,3525 149 3 341,1 340,8 0,3410 160 157 3 341,1 340,8 0,3402 160 157 3 342,3 343,7 0,3430 158 157 1 362,0 363,9 0,3629 141 140 BM 2 2 363,9 371,5 0,3668 138 140 BM 2						154		
5 344,4 343,8 0,3441 157 1 332,3 330,6 0,3315 169 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 2 353,1 352,0 0,3525 149 3 341,1 340,8 0,3410 160 157 3 341,1 340,8 0,3410 160 157 HAZ 2 4 340,8 339,5 0,3402 160 157 HAZ 2 4 340,8 339,5 0,3629 141 2 363,9 371,5 0,3677 137 1 365,7 367,8 0,3668 138 140 BM 2 4 363,4 365,7 0,3646						154		HAZ 1
1 332,3 330,6 0,3315 169 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 2 353,1 352,0 0,3525 149 3 341,1 340,8 0,3410 160 157 3 341,1 340,8 0,3402 160 157 4 340,8 339,5 0,3402 160 157 3 342,3 343,7 0,3430 158 140 HAZ 2 2 363,9 371,5 0,3677 137 3365,7 367,8 0,3668 138 140 BM 2	2.6876				0.01129/0200		-	1
2 333,3 334,8 0,3341 166 3 338,9 336,3 0,3376 163 4 335,2 334,0 0,3346 166 5 335,2 334,0 0,3349 166 5 335,2 335,8 0,3355 165 1 345,6 344,1 0,3449 156 2 353,1 352,0 0,3525 149 3 341,1 340,8 0,3410 160 5 342,3 343,7 0,3430 158 1 362,0 363,9 0,3629 141 2 363,9 371,5 0,3668 138 140 BM 2 4 363,4 365,7 0,3646								
3 338,9 336,3 0,3376 163 166 WM 4 335,2 334,0 0,3346 166 <								1
5 335,2 335,8 0,3355 165 1 345,6 344,1 0,3449 156 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 2 363,9 371,5 0,3677 137 3 365,7 367,8 0,3668 138 140 BM 2		338,9				166		WM
1 345,6 344,1 0,3449 156 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 2 363,9 371,5 0,3677 137 3 365,7 367,8 0,3668 138 140 BM 2 BM 2								1
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 2 363,9 371,5 0,3668 138 3 365,7 367,8 0,3668 138 4 363,4 365,7 0,3646 140	1070							1
3 341,1 340,8 0,3410 160 157 HAZ 2 4 340,8 339,5 0,3402 160 1				a set of the set of th				4
4 340,8 339,5 0,3402 160 5 342,3 343,7 0,3430 158 1 362,0 363,9 0,3629 141 2 363,9 371,5 0,3677 137 3 365,7 367,8 0,3668 138 140 4 363,4 365,7 0,3646 140 BM 2						157		НА7 2
5 342,3 343,7 0,3430 158 1 362,0 363,9 0,3629 141 2 363,9 371,5 0,3677 137 3 365,7 367,8 0,3668 138 140 4 363,4 365,7 0,3646 140 BM 2								
1 362,0 363,9 0,3629 141 2 363,9 371,5 0,3677 137 3 365,7 367,8 0,3668 138 4 363,4 365,7 0,3646 140	1000					1		1
3 365,7 367,8 0,3668 138 140 BM 2 4 363,4 365,7 0,3646 140 EM 2	1	362,0	363,9	0,3629	141			
4 363,4 365,7 0,3646 140								1
						140		BM 2
								1
		000,0	000,0	0,0070	140			
Date: 06.11.22 Tester: Scheck								

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

\mathbb{N}	STUTTG	ART	MP	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000					
Sample desc	ription	23C.2; Out	er layer				
Administrato	or	Silcher					
Test instrum		Zwick Z 323	(neu)				
			10-727 - SP Share - Weiges				
Serial numbe		H2932-002-	50430				
Test conditio	ns						
I HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
1100000000							
HRC	Constant and	DIN EN ISO					
	A CHOOR CLASSES	peratur, if out	I DORANG DE REALEMENTERS				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	122-03-03-03-03-0		
Indentation no.	d,	d ₂	dm	Hardness HV	Mean value HV	Distance in mm	Remark
10.	μm	μm	mm	nv	HV .	mm	
1	353,7	358,0	0,3559	146			
2	346,4	349,1	0,3478	153			1
3	354,5	359,3	0,3569	146	148		BM 1
4	352,9	359,1	0,3560	146 147			
5	354,1 332,8	356,4 §§=;\$	0,3552 0,3328	147			
2	331,9	329,6	0,3308	170			
3	330,6	330,8	0,3307	170	170		HAZ 1
4	333,1	329,6	0,3314	169			
5	327,3	329,0	0,3282	172			
1	316,4 324,2	321,5 318,6	0,3189 0,3214	182 180			
3	324,2	315,9	0,3214	183	182		WM
4	322,1	320,5	0,3213	180			
5	320,7	315,7	0,3182	183			
1	347,0	342,9	0,3450	156			
2	344,1 339,2	344,1 339,6	0,3441 0,3394	157 161	159		HAZ 2
4	343,9	336,7	0,3394	160	139		
5	340,8	340,4	0,3406	160			1
1	354,3	359,9	0,3571	145			
2	357,6	364,3	0,3609	142			
3	357,2	358,9	0,3580	145	145		BM 2
4	355,3 353,9	361,6 358,0	0,3585 0,3560	144 146			
5	000,0	000,0	0,0000	1.10			
Date:	06.11.22						
Tester:	Scheck						



\mathbb{N}	STUTTG,	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	iption	23C.2; Roo	t				
Administrate	nr.	Silcher					
	22						
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC	6506-1:201	5-02			
A Carlos and							
HRC	State of States	DIN EN ISO					
		eratur, if out					
Control plate	280,6	280,8	0,281	235		Reference:	237 HV 10
	μm	μm	mm	HV	The set of carries	D ¹ · · · · ·	
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
		P					
1	342,5	346,2	0,3444	156			2
2	343,9	350,4	0,3472	154	1000		
3	350,6	350,8	0,3507	151	152		BM 1
4	354,1	353,7	0,3539	148			
5	349,6 330,9	352,7 329,8	0,3511 0,3303	150 170			
2	344,6	343,1	0,3438	157	1 1		
3	354,1	351,4	0,3528	149	156		HAZ 1
4	354,7	351,8	0,3533	149			
5	347,9	346,8	0,3474	154	1 1		
1	335,8	333,1	0,3345	166			
2	335,0	329,2	0,3321	168	all and the second		
3	335,2	330,6	0,3329	167	168		WM
4	329,8	326,5	0,3282	172			
5	333,1	329,6 342,3	0,3314	169		-	-
2	347,5 344,3	342,3	0,3449 0,3423	156 158	1 1		
3	348,7	340,2	0,3423	154	155		HAZ 2
4	347,3	343,1	0,3452	156			
5	350,2	346,0	0,3481	153			
1	348,1	353,3	0,3507	151			
2	346,2	349,5	0,3479	153	1922-2		
3	348,9	351,4	0,3502	151	152		BM 2
4	346,2 340,8	352,0 351,0	0,3491 0,3459	152 155		1	
	540,0	551,0	0,0400	155			·
Date:	06.11.22					<u>4. (</u>	
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 Sp	pecial 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

Chamies Leanna sitism	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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.

- 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

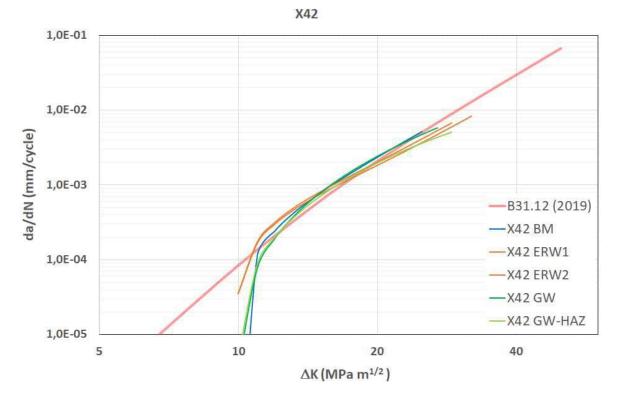


Figure 3.22: Crack growth X42

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.

\mathbb{N}	STUTTGA	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	per	9039784000)				
Sample desc	ription	3LN-1 Oute	er layer				
Administrat	or	Silcher					
Test instrun	nent	Zwick Z 323	(neu)				
Serial numb		H2932-002-	1911 - E2				
		H2932-002-	50430				
Test condition							
🖸 HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou					
Control	280,6	280,8	0,281	235			Lange and the
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Kemark
				100			
1	312,4 312,6	319,0 318,0	0,3157 0,3153	186 187			
3	310,3	316,9	0,3135	189			
4	308,8	316,1	0,3125	190			
5	309,3	314,7	0,3120	191		-	1
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 11	308,9 309,7	312,8 313,4	0,3108 0,3116	192 191			-
12	310,1	312,0	0,3110	191			
13	311,3	313,0	0,3112	192			1
14	311,5	311,1	0,3113	191			1
15	305,7	303,3	0,3045	200			1
16	305,5	305,7	0,3056	199			
17	310,5	312,6	0,3116	191			4
18	311,3	312,6	0,3120	191			
19 20	310,1 311,1	312,6 314,0	0,3113 0,3126	191 190			
20	311,6	314,0	0,3120	190			1
22	309,9	312,0	0,3109	192			1
23	306,8	309,9	0,3083	195]
							4
		-					
And a state of the	in the second						1
Date:	06.11.22						
	e. 1						
Tester:	Scheck						

Figure 3.23: Hardness measurements of X42 (1)

\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	3 LN-1 Ro	ot				
Administrat	or	Silcher					
Test instrum		Zwick Z 323	(neu)				
			23				
Serial number		H2932-002-	50430				
Test conditio	ins						
🗹 HV 🕐	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou					
Control	280,6	280,8	0,281	235		1000	lane concerna.
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	A CONTRACTOR
1	311,5	318,2	0,3149	187			
2	313,0	320,1	0,3165	185			1
3	317,4	321,5	0,3194	182			1
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 8	319,9 320,5	324,4 325,2	0,3221 0,3229	179 178			-
9	320,5	323,0	0,3229	178			
10	318.6	324,2	0,3214	180			1
11	318,0	322,3	0,3202	181			
12	318,4	321,7	0,3201	181	1		1
13	317,0	314,0	0,3155	186]
14	311,6	311,1	0,3113	191	1		1
15	320,5	322,3	0,3214	180			4
16	319,0	320,9	0,3200	181			4
17 18	317,6 317,8	321,7 321,3	0,3196 0,3195	181 182			4
19	318,8	321,3	0,3195	182			1
20	320,3	322,5	0,3203	180	1		1
21	319,6	322,1	0,3209	180	1 1		1
22	313,2	317,8	0,3155	186			1
			-				
Date:	06.11.22						
Tester:	Scheck						
rester:	Scheck						

Figure 3.24: Hardness measurements of X42 (2)

\mathbb{N}	STUTTG		M	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat ographie und enmikroskopie
Order numb	ber	9039784000)				
Sample desc	ription	3 LN-2 Out	er layer	a series of	a di secondari		
Administrat	or	Silcher					
Test instrum	ont	Zwick Z 323	(neu)				
			75				
Serial numb		H2932-002-	50430				
Test conditio	ons						
HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
1111 11134 1230			6508-1:201				
	A CHOOL SHOOL	peratur, if ou	STREET, SOUTH STREET, S				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	The second second second		
Indentation no.	d,	d ₂	dm	Hardness HV	Mean value HV	Distance in mm	Remark
110.	μm	μm	mm	nv	HV	mai	
া	308,4	314,3	0,3113	191		1	-
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	194 188			-
7	312,8 310,3	315,1 311,3	0,3139 0,3108	192			
9	310,5	312,2	0,3103	192			1
10	310,7	311,5	0.3111	192			
11	306,8	311,3	0,3091	194			1
12	307,6	310,3	0,3090	194			1
13	301,8	301,0	0,3014	204]
14	307,4	304,5	0,3059	198			4
15	309,9	313,8	0,3119	191			4
16 17	310,1 308,6	313,0 313,6	0,3116 0,3111	191 192			4
17	310,7	313,6	0,3118	192			1
19	312,6	315,1	0,3138	188			1
20	312,6	315,3	0,3139	188			1
21	312,4	315,7	0,3140	188]
22	310,7	315,3	0,3130	189			1
23	311,6	316,5	0,3140	188			4
24	313,6	318,4	0,3160	186			1
							·
Date:	06.11.22						
Tester:	Scheck						

Figure 3.25: Hardness measurements of X42 (3)

\mathbb{N}	STUTTGA		MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	3 LN-2 Ro	ot		and State day.		
Administrat	or	Silcher					
Test instrum	72	Zwick Z 323	(nou)				
			11. 12 				
Serial numb		H2932-002-	50430				
Test conditio	ons						
HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508 1-201	6 12			
	Tertter	peratur, if ou					
	SAGED Del Decros	Contraction of the second sectors	ALCONTROL MANY CONTROL			1.00-	The second second second
Control plate	280,6	280,8	0,281	235 HV		Reference:	237 HV 10
	_µm d₁	μm d ₂	mm d _m		Maanarahus	Distance in	
Indentation no.	un un	μm	mm	Hardness HV	Mean value HV	mm	Remark
1171		Part					
1	306,4	314,0	0,3102	193			
2	306,8	314,2	0,3105	192]		
3	307,8	313,4	0,3106	192	1 1		
4	308,4	312,8	0,3106	192	4		
5	310,5 314,7	312,6 318,8	0,3116 0,3167	191 185	4		
7	314,7	320,3	0,3107	183	1		
8	319,9	322,3	0,3211	180	1 1		
9	318,2	322,4	0,3203	181	1		
10	318,0	320,9	0,3194	182	1		
11	319,2	320,3	0,3198	181] [
12	318,6	320,7	0,3196	181	1 1		
13	321,9	323,0	0,3224	178	4		
14 15	315,9 319,8	313,8 318,2	0,3149 0,3190	187 182	4		
15	317,4	322,8	0,3190	182	1		1
17	320,3	323,8	0,3220	179	1		
18	319,4	323,0	0,3212	180	1 I]
19	320,3	323,2	0,3217	179	1 1		
20	320,1	321,1	0,3206	180	4		1
21 22	317,8	323,2 323,0	0,3205 0,3195	181 182	4		
22	316,1 316,3	323,0	0,3195	182	1		
23	314,7	323,2	0,3189	182	1		
						-	
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

	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

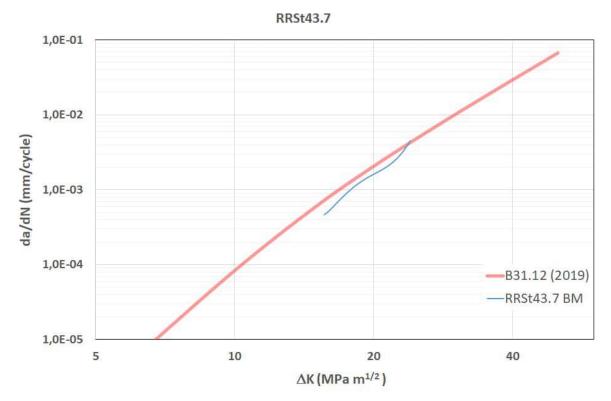


Figure 3.27: Crack growth RRSt43.7

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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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_{JIc} [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.

 $^{^{\}rm 6}$ V-sample as per DIN EN ISO 148-1 at -50 $^{\circ}{\rm C}$

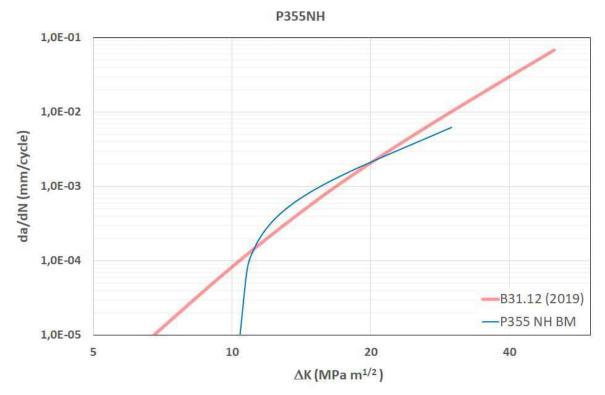


Figure 3.28: Crack growth P355 NH

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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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 $^\circ\text{C}$

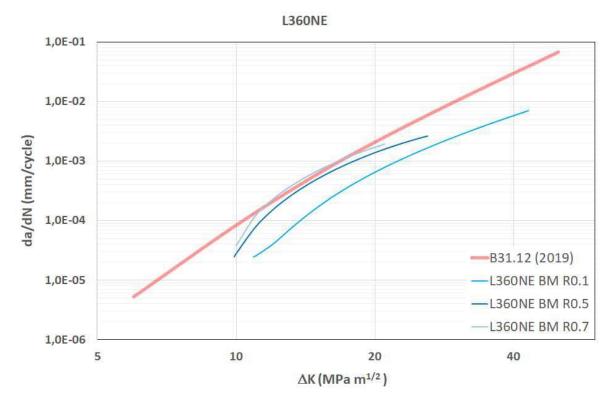


Figure 3.29: Crack growth L360 NE

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		
	Κ _v [J]	145		

Table 3.29: Chemical composition of L360NB

	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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_{Jlc} [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.

- base material
- weld material

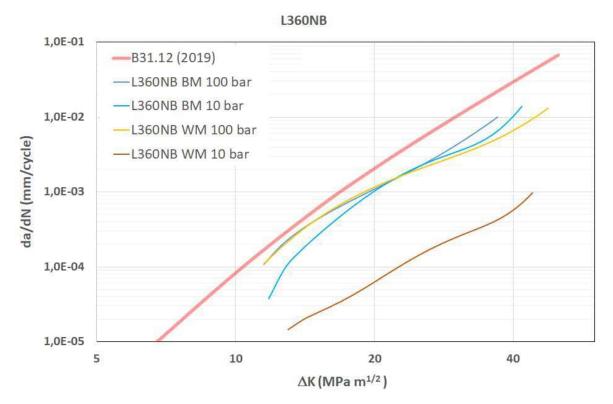


Figure 3.30: Crack growth L360NB

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
	Κ _v [J]	Ø 107

Table 3.32: Chemical composition of X46 / StE320.7

Ohamiaal	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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 _{Jlc} [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.

- base material
- weld material of the girth weld

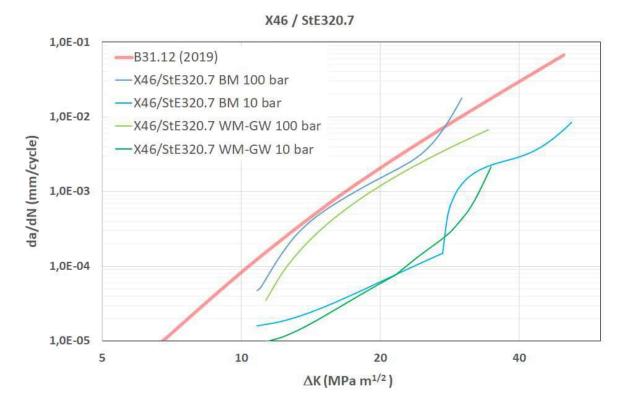


Figure 3.31: Crack growth X46 / StE320.7

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

	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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).

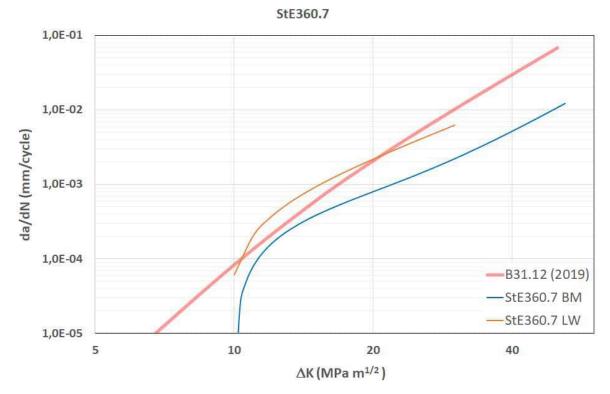


Figure 3.32: Crack growth StE360.7

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.

\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	18.1; Outer	layer				
Administrato	or	Silcher					
Test instrum	ant	Zwick Z 323	(neu)				
Serial numbe		H2932-002-					
		112952-002-	30430				
Test conditio							
U HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou	tside (23+/	-5) °C			
Control	280,6	280,8	0,281	235		D-f-	
plate	μm	μm	mm	HV		nererence:	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Action
	292,5	300,8	0,2966	211			-
2	293,9	301,6	0,2900	209		1	
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	218 221			
8	286,9 285,6	292,7 291,0	0,2898 0,2883	221			
10	285,6	291,0	0,2883	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		-	1
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 19	287,9 289,6	288,7 293,1	0,2883	223 219			
20	289,0	293,1	0,2913	219			
21	287,9	290,2	0,2890	222			
22	287,9	283,6	0,2857	227			
						-	
Date:	06.11.22			9-m		· · · · · · · · · · · · · · · · · · ·	5-11.
Tester:	Scheck						
	- and an						

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

	STUTTGA	RT	MPAS-PPB 523 Hardness			Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	18.1; Roo	t				
Administrato	or	Silcher					
Test instrum	ent	Zwick Z 323	(neu)				
Serial numbe		H2932-002-					
Test conditio	ns						
	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO					
HRC		DIN EN ISO					
	Test tem	peratur, if ou					
Control	280,6	280,8	0,281	235		Rafarance	237 HV 10
plate	μm	μm	mm	HV		Reference;	237 HV 10
Indentation	d,	d₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	
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			4
5	294,9	305,1	0,3000	206			
6 7	293,3 295,8	304,7 303,0	0,2990	207 207			4
8	295,8	302,2	0,2994	207			
9	293,3	300,3	0,2968	210			1
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			4
15 16	288,3 294,9	294,5 298,7	0,2914	218 210			
10	294,9	298,7	0,2968	210			
18	293,9	301,8	0,2979	209			
19	291,2	296,8	0,2940	215			1
20	291,4	298,5	0,2949	213			
					[
							4
		-					
	06.11.22 Scheck						

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

\mathbb{N}	STUTTG	ART	M	Test rep PAS-PPB 523 Hardness	310-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	18.2; Outer	layer				
Administrato	r	Silcher					
Test instrum	ent	Zwick Z 323	(neu)				
Serial numbe		H2932-002-	10 E				
		112332-002-	50450				
Test conditio							
⊡ HV ·	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC	6506-1:201	5-02			
HRC		DIN EN ISC	6508-1:201	6-12			
	Test ten	nperatur, if o	utside (23+/	45) °C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		nererence.	237 HV 10
Indentation no.	d₁ µm	dz µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
		000 7	0.0015				
1	290,4 288,7	292,7 292,9	0,2915 0,2908	218 219		1	
3	284,8	290,8	0,2878	213			
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	281,0 282,3	286,9 288,5	0,2839 0,2854	230 228			
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 14	286,6 287,5	292,7 293,3	0,2897 0,2904	221 220			
14	287,5	293,3	0,2904	220			
16	288,7	295,8	0,2922	217		i 	1
17	291,0	297,2	0,2941	214			
18	292,7	297,0	0,2948	213		-	
19	296,8	302,8	0,2998	206			
]
		1					
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}			м	Test re PAS-PPB 523 Hardnes	310-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	18.2; Root	t				
Administrato	or	Silcher					
Test instrum	ent	Zwick Z 323	(neu)				
Serial numbe	r	H2932-002-	18 - 230 19 (19 19 19 19 19 19 19 19 19 19 19 19 19				
Test conditio	ins						
	10	DIN EN ISO	6507 1-201	9.07			
HBW	10	DIN EN ISO		Side a			
HRC	Test ten	DIN EN ISO operatur, if o					
Control	280,6	280,8	0,281	235		156949	Deneration of
Control plate	280,6 µm	μm	mm	HV		Reference:	237 HV 10
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	294,3 293,5	300,3 301,0	0,2973 0,2972	210 210			
3	296,6	301,0	0,2972	208			
4	294,7	300,6	0,2976	209	1 1		
5	292,0	299,7	0,2959	212			
6 7	292,9 293,1	298,7 298,5	0,2958	212 212			
8	290,2	296,2	0,2932	212			
9	288,9	296,6	0,2928	216	1 1		
10	288,9	296,2	0,2926	217	1 [
11	278,8	276,3	0,2775	241			
12 13	292,3 290,0	299,5 298,7	0,2959	212 214			
14	291,4	301,4	0,2943	214			
15	296,4	304,7	0,3006	205			
16	294,9	303,0	0,2990	207			
17 18	292,9 293,9	302,2 303,0	0,2975 0,2985	209 208			
19	292,7	304,3	0,2985	208			
						_	
	-						
		1					
							1
	_	-	_	-			
Date:	06.11.22						
Terter	Cohort						
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	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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.

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

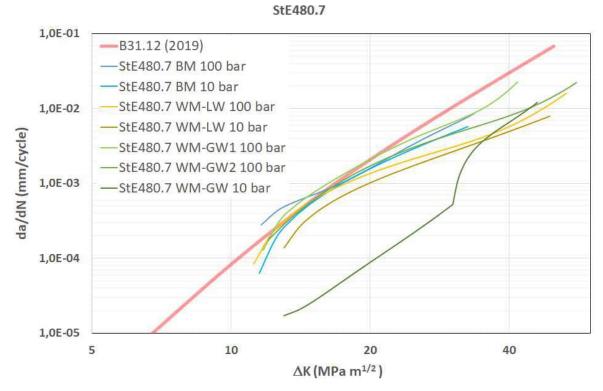


Figure 3.37: Crack growth StE480.7 TM

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	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

Ob anni a la anna a iti an	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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

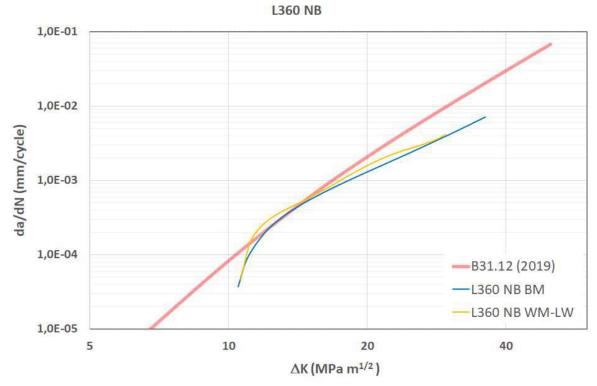


Figure 3.38: Crack growth L360 NB

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.

	STUTTG	RT	MP	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000					
Sample descr	iption	20HFLN-1;	Outer layer				
Administrato		Silcher					
electron and the second second							
Test instrum	trument Zwick Z 323 (neu)						
Serial numbe	er	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISO	6507-1-201	8-07			
□ HBW		DIN EN ISO					The party of the second
HRC		DIN EN ISO					
	Test tem	peratur, if ou	tside (23+/-	-5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	2040/2020/002
1	293	301	0,2970	210 209			
2	294,5 270,7	301,4 280,6	0,2980 0,2756	209			
4	262.2	263,6	0.2629	268			1
5	262,8	265,1	0,2639	266			1
6	259,9	261,9	0,2609	272			1
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 11	255,7	255,7	0,2557	284 270			
12	264,5 270,0	259,4 273,4	0,2620	270			
13	275,0	275,6	0,2753	245			1
14	285,4	289,6	0,2875	224			1
15	292,2	293,1	0,2927	216]
16	293,5	296,0	0,2947	213			1
17	291,4	291,8	0,2916	218			4
18	290,6 295,4	292,0 291,2	0,2913	219 216			4
19 20	295,4	291,2	0,2933	210			1
20	289,8	293,3	0,2915	213			1
22	291,2	291,8	0,2915	218			1
23	287,1	290,6	0,2888	222			1
24	287,9	287,3	0,2876	224			1
25	291,0	291,4	0,2912	219			4
26 27	292,7	295,8	0,2942	214			{
	295,4	299,1	0,2972	210			
	06.11.22 Scheck						

Figure 3.39: Hardness measurements of L360 NB (1)

\mathbb{N}	STUTTG		MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	mple description 20HFLN-1						
Administrato							
Test instrum		Zwick Z 323	(nou)				
					CONTRACTOR OF THE OWNER		MARCH CONTRACTOR
Serial numbe	r	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
		DIN EN ISO	6508-1-201	6_12			
HRC	Test tem	peratur, if ou					
Contrat	280,6	280,8	0,281	235		19960	Television and
Control plate	280,6 µm	280,8 µm	0,281 mm	HV 235		Reference:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	
no.	μm	μm	mm	HV	HV	mm	Remark
1	290,0	300,1	0,2951	213			
2	283,9	294,5	0,2892	222			
3	283,7 282,7	286,4 286,4	0,2851 0,2846	228 229			
5	281,7	285,6	0,2836	223			
6	276,1	279,4	0,2777	240	1 1		
7	266,1	267,3	0,2667	261	1 1		1
8	255,5	259,0	0,2573	280	1 1		
9	251,2	259,4	0,2553	285	1 1		1
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 14	291,6	294,3	0,2930	216 206			
14	297,9 298,9	301,8 299,7	0,2998 0,2993	206			
16	299,3	302,0	0,2993	207			1
17	298,5	301,8	0,3001	206			1
18	298,7	303,9	0,3013	204	1 1]
19	302,4	299,9	0,3012	204	1 1		
20	299,9	303,2	0,3016	204	[
21	302,2	302,2	0,3022	203			
22 23	302,6	305,7 306,2	0,3042 0,3047	200 200			4
23	303,2	500,2	0,3047	200			
		ļ					
Date:	06.11.22						
Tester	Cabard						
Tester:	Scheck						

Figure 3.40: Hardness measurements of L360 NB (2)

\mathbb{N}	STUTTG		MF	Test rej PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie	
Order numb	er	9039784000)					
Sample descr	iption	20HFLN-2,	Outer laver					
Administrato		Silcher						
Test instrum		Zwick Z 323	(neu)					
Serial numbe	r	H2932-002-	50430					
Test conditio	ns							
	10	DIN EN ISO	6507-1.201	8-07				
Phil I Humanaway		Carl Martin College						
HBW		DIN EN ISO						
HRC		DIN EN ISO					en ander verste en	
	Test tem	peratur, if ou	tside (23+/-	·5) *C				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
plate	μm	μm	mm	HV				
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm		
1	294,3	295,2	0,2947	213				
2	295,2	295,2	0,2953	213	1			
3	288,9	291,6	0,2903	220	1			
4	284,4	287,7	0,2860	227	1			
5	288,7	288,3	0,2885	223	4			
6 7	289,4 290,2	285,8 294,1	0,2876	224 217	4			
8	290,2	294,1	0,2921	217	1			
9	289,1	293,3	0,2912	219				
10	288,7	288,9	0,2888	222	1			
11	292,0	294,3	0,2932	216	1		1	
12	289,8	294,3	0,2920	217				
13 14	287,7	288,5	0,2881	223 237	4			
14	279,2 264,9	280,6 272,7	0,2799 0,2688	237	1 1			
16	260,9	265,3	0,2631	268	1	-		
17	253,0	254,3	0,2537	288]			
18	255,5	259,5	0,2575	280	1 1			
19	254,9	258,6	0,2568	281				
20 21	255,7 261,7	256,1 261,9	0,2559 0,2618	283 270				
21	268,6	266,9	0,2678	259	1			
23	268,4	268,2	0,2683	258]		1	
24	268,2	278,3	0,2733	248				
Date:	06.11.22							
Tester:	Scheck							
-corer:	Geneen							

Figure 3.41: Hardness measurements of L360 NB (3)

V	STUTTGA	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	20HFLN-2;	Root				
Administrato	or	Silcher					
Test instrum			(
		Zwick Z 323			CONTRACTOR OF		
Serial numbe	r	H2932-002-	50430				
Test conditio	ns						
I HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1-201	6-12			
	Test ten	peratur, if o					
Control	280,6	280,8	0,281	235		D-6	
plate	μm	μm	mm	HV		Keference:	237 HV 10
Indentation no.	d,	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
10.	μm	pm	mm	nv	nv		
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	304,9 304,5	306,6 305,3	0,3057 0,3049	198 199		1	
6	304,5	303,2	0,3043	203		N	
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	206 216			
12 13	291,4 283,3	294,3 283,1	0,2929 0,2832	216		-	
14	275,0	272,3	0,2032	248	1 1		
15	261,3	264,6	0,2630	268	1		1
16	254,7	257,2	0,2559	283			
17	254,7	256,8	0,2557	284			
18 19	265,9 273,8	267,8 279,2	0,2668	260 243			
20	273,8	279,2	0,2765	243			
21	285,4	289,3	0,2874	225	1		
22	283,3	287,7	0,2855	228	1 1		
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

Ohamiaal	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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.

- base material
- longitudinal weld
- girth weld

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

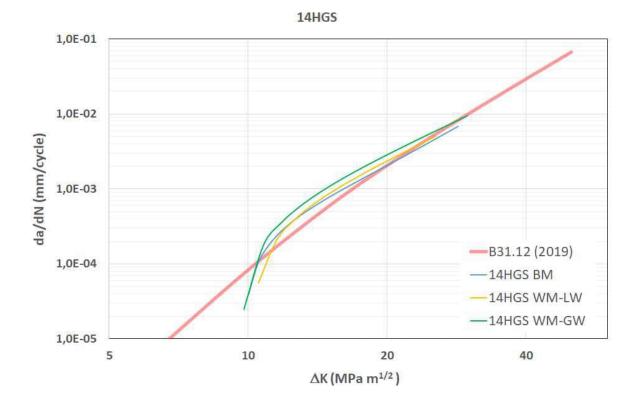


Figure 3.43: Crack growth 14HGS

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.

\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	21LN-1; Ou	ter layer		All		
Administrato	r	Silcher					
Test instrume			(2011)		a Charles	CORRECT OF	Contraction of the second
		Zwick Z 323					
Serial numbe	r	H2932-002-	50430			No. 2 and Co. 2.	
Test conditio	ns						
⊡ HV 1	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC					
HRC	12 COLORADO	DIN EN ISO					
	A CHOOM DURING	iperatur, if ou	BIDOSCIUS MACEORI	-5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	source workers
1	330,6	327,1	0,3289	171			
2	329,2	331,3	0,3302	170	1 1		
3	331,9	334,2	0,3330	167	168		BM 1
4	335,2	335,6	0,3354	165	1 [
5	333,1	333,6	0,3333	167			
1	308,4	308,0	0,3082	195 204			HAZ 1
2	302,2 294,3	301,4 299,3	0,3018	204	208		
4	294,5	292,0	0,2908	210	200		
5	294,5	294,9	0,2947	213			
1	329,4	329,8	0,3296	171			
2	332,7	331,9	0,3323	168			1
3	329,6	326,7	0,3282	172	171		WM
4	322,2	322,4	0,3223	179			
5	333,3	333,6	0,3334	167			
1	313,8	313,0	0,3134	189			4
2	304,3 297,6	303,0 299,5	0,3037 0,2986	201 208	204		HAZ 2
4	297,0	300,5	0,2988	208	204		
5	294,5	292,0	0,2933	216			
1	328,6	327,8	0,3282	172			
2	324,4	324,0	0,3242	176			1
3	326,3	325,2	0,3258	175	173		BM 2
4	327,7	328,6	0,3282 0,3297	172			4
5	331,1	328,4	0,3297	171			
Date: (06.11.22						
Tester:	Scheck						



\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000	Ì				
Sample descr	iption	21LN-1; Cer	nter		all the	All Marson	
Administrato	r	Silcher					
Test instrume		Zwick Z 323	(neu)				
Serial numbe	r	H2932-002-	50430				
Test condition	ns						
⊡ HV 1	10	DIN EN ISO	6507-1-201	8-07			
No. Contractory		TEMAN PEAK SCROOT					
HBW		DIN EN ISO					
HRC		DIN EN ISO			and an		
	Test tem	peratur, if ou	tside (23+/-	5) *C			
Control	280,6	280,8	0,281	235		References	237 HV 10
plate	μm	μm	mm	HV		neierence.	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	
1	326,1	330,0	0,3281	172			
2	332,3	331,5	0,3281	168	ł ł	1	
3	333,8	330,6	0,3322	168	167		BM 1
4	334,6	340,0	0,3373	163			Divi 1
5	335,6	337,1	0,3364	164			
1	301,0	296,4	0,2987	208			
2	300,8	300,8	0,3008	205	100		
3	302,0	301,6	0,3018	204	199		HAZ 1
4	308,2 321,7	305,7 319,0	0,3070 0,3204	197 181			
1	340,2	332,1	0,3204	164			
2	331,5	330,0	0,3307	170			
3	333,8	330,6	0,3322	168	168		WM
4	332,5	333,3	0,3329	167			
5	330,6	326,3	0,3285	172	1 [
1	303,5	298,7	0,3011	205			
2	304,7	297,2	0,3010	205			
3	303,5	304,9	0,3042	200	202		HAZ 2
4	298,7	299,5	0,2991	207			
5	309,7 332,7	308,2 338,8	0,3090	194 165			
2	327,1	334,4	0,3308	169		-	
3	327,1	331,5	0,3293	171	169		BM 2
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)

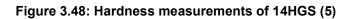
\mathbb{N}	STUTTGA	ART	MP	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie				
Order numb	er	9039784000)								
Sample desc	ription	21LN-1; R			and the	CONTRACT.					
Administrato	or		001								
		Silcher									
Test instrum	ent	Zwick Z 323	(neu)								
Serial numbe	er	H2932-002-	50430								
Test conditio	ns										
U HV	10	DIN EN ISO	6507-1.201	8-07			The second second				
HBW			DIN EN ISO 6507-1:2018-07 DIN EN ISO 6506-1:2015-02								
HRC			DIN EN ISO 6508-1:2016-12								
	Test ter	peratur, if ou									
Control	280,6	280,8	0,281	235		1000	Parete 1200-50				
plate	280,0 µm	μm	0,201 mm	HV		Reference:	237 HV 10				
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Destruction				
no.	μm	μm	mm	HV	HV	mm	Remark				
	220.2	224.2	0.2202	170		-					
2	329,2 326,1	331,3 326,3	0,3302 0,3262	170							
3	331,9	331,1	0,3315	169	170		BM 1				
4	327,1	333,4	0,3302	170			DIVI I				
5	331,1	333,5	0,3323	168							
1	315,7	314,9	0,3153	187							
2	295,4	296,2	0,2958	212	0.000000		HAZ 1				
3	299,9	300,1	0,3000	206	193						
4	320,7	312,2	0,3164	185							
5 1	327,1 336,7	326,5 336,5	0,3268	174 164							
2	333,1	329,4	0,3313	169							
3	333,2	327,7	0,3305	170	167		WМ				
4	334,2	329,8	0,3320	168							
5	337,1	333,1	0,3351	165							
1	309,1	307,0	0,3080	195							
2	312,6	310,1	0,3113	191	100						
3	315,5	310,1 308,6	0,3128 0,3095	190 194	190		HAZ 2				
4	310,3 323,2	308,6	0,3095	194							
1	331,3	327,3	0,3293	170							
2	321,9	325,2	0,3236	177							
3	324,0	325,0	0,3245	176	175		BM 2				
4	324,3	328,6	0,3264	174							
5	325,9	324,0	0,3250	176							
Date:	06.11.22	1									
Tester:	Scheck										

Figure 3.46: Hardness measurements of 14HGS (3)

\mathbb{N}	STUTTGA	RT	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	21LN-2, Ou	ter layer			All and a second	
Administrato	or	Silcher			and the second	C. C. S. S. S.	
Toet instrum	ant		(mar)				
Test instrument Zwick Z 323 (neu)					and the second		
Serial numbe	21	H2932-002-	50430				
Test conditio	ns						
I HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC							
	T 245 12	DIN EN ISO					
		peratur, if ou				0.00-	Transformer and the second
Control plate	280,6	280,8	0,281 mm	235 HV		Reference:	237 HV 10
Indentation	_µm d₁	μm d ₂	d _m	Hardness	Mean value	Distance in	
no.	μm	μm	mm	Hardness	HV	mm	Remark
	1	Part					
1	310,1	308,9	0,3095	194			9 1.
2	312,8	310,5	0,3117	191	192		1
3	310,7	308,4	0,3096	193			BM 1
4	310,9	314,3	0,3126	190			
5	312,0	312,6	0,3123	190 227			
1	287,3 279,6	284,6 281,9	0,2859 0,2807	235			1
3	279,8	280,4	0,2801	236	231		HAZ 1
4	284.2	286,6	0,2854	228			
5	286,6	283,9	0,2853	228			
1	322,3	314,2	0,3183	183			
2	318,4	313,8	0,3161	186			
3	321,7	312,8	0,3173	184	186		WM
4	312,8	301,2	0,3070	197	4		4
5	317,8 284,4	319,9 285,8	0,3188 0,2851	182 228			
2	287,1	282,1	0,2846	229	1		1
3	282,7	285,4	0,2841	230	225		HAZ 2
4	288,9	288,7	0,2888	222			1
5	292,9	290,2	0,2915	218			
1	312,6	314,0	0,3133	189			
2	312,0	314,3	0,3131	189	106		
3	318,4 315,7	315,1 315,3	0,3167 0,3155	185 186	186		BM 2
5	317,6	319,2	0,3133	183			
	0						
Date:	06.11.22						
Tester:	Scheck						

Figure 3.47: Hardness measurements of 14HGS (4)

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat ographie und enmikroskopie
Order numb	er	9039784000	D				
Sample descr	iption	21LN-2, Ce	nter		state and the	du.	
Administrato	r	Silcher					
Test instrum	ant	Zwick Z 323					
Serial numbe	r	H2932-002-	50430				
Test conditio	ns						
J HV ·	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC	6506-1-201	5-02			
HRC				1. (1997)			
	Tertter	DIN EN ISO					
	A CHOOM SPROOT	peratur, if ou	STOCKED AND COMP	NAMES OF A DESCRIPTION OF			
Control plate	280,6	280,8	0,281	235		Reference:	237 HV 10
	μm	μm	mm	HV	Mannahus	Distance in	
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
	Part	- p					
1	323,9	329,6	0,3267	174			
2	325,9	327,7	0,3268	174	176		
3	322,1	327,7	0,3249	176			BM 1
4	318,4	322,8	0,3206	180			
5	322,4 290,0	326,1 293,3	0,3242 0,2916	176 218			
2	290,0	293,3	0,2910	210			
3	295,4	299,1	0,2972	210	212		HAZ 1
4	296,2	299,1	0,2976	209			
5	299,5	299,3	0,2994	207	1 1		1
1	330,2	330,9	0,3305	170			
2	330,2	326,9	0,3286	172			
3	330,3	327,9	0,3291	171	171		WM
4	336,0 328,2	323,4 333,4	0,3297 0,3308	171 170			4
5	292,7	296,0	0,3308	214			
2	297,2	299,1	0,2943	209	1 1		1
3	296,8	297,8	0,2973	210	210		HAZ 2
4	297,9	297,8	0,2979	209	antropy (1997)]
5	298,1	301,2	0,2996	207			
1	329,4	331,7	0,3305	170			1
2	326,3	330,6	0,3285	172	170		
3	326,7 326,5	329,4 327,3	0,3281	172 174	172		BM 2
4	326,5	327,3	0,3269 0,3287	174	1 1		1
		1					
Date:	06.11.22	•					
Tester:	Scheck						



\mathbb{N}	STUTTGA		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	21LN-2; R	oot		15	All the second second	
Administrato	or	Silcher					A Strength
Storn Managements							
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er.	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07			
□ HBW		DIN EN ISC	55.56 (1/55.56)	Constant and the			
HRC	Test tem	DIN EN ISO peratur, if ou	6508-1:201 Itside (23+A				
Control	280,6	280,8	0,281	235		1000	lesson and
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	(Produced)
no.	μm	μm	mm	HV	HV	mm	Remark
1	312,0	316,7	0,3144	188			
2	310,1	312,8	0,3115	191	190		
3	309,7 310,1	313,2 313,0	0,3114 0,3116	191 191			BM 1
5	315,1	312,0	0,3135	189			
1	306,8	302,0	0,3044	200			-
2	294,5	292,5	0,2935	215			HAZ 1
3	295,6	300,1	0,2979	209	203		
4	307,4	308,8	0,3081	195			
5	307,4	305,7	0,3066	197			
1	334,6	326,1	0,3303	170			
2	333,8	332,1	0,3329	167 171	169		wм
3	331,7 332,7	326,9 330,7	0,3293 0,3317	169	109		
5	336,0	330,0	0,3330	167			
1	303,7	301,2	0,3024	203			
2	305,1	304,5	0,3048	200		l.	
3	307,6	309,1	0,3083	195	199		HAZ 2
4	304,3	301,2	0,3027	202			
5	310,5	308,6	0,3096	193		·	
1	321,3 316,1	320,9 315,9	0,3211 0,3160	180 186			
2	312,8	316,9	0,3160	187	184		BM 2
4	317,4	317,6	0,3145	184	10-		
5	316,5	317,6	0,3171	184			
Date:	06.11.22						
Tester:	Scheck						

Figure 3.49: Hardness measurements of 14HGS (6)

\mathbb{N}	STUTTG	ART	M	Test rep PAS-PPB 523 Hardness	10-08/1	Metallog	ferat graphie und nmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	21 UN (2); (Outer layer				
Administrato	-	Silcher					
Test instrume		Zwick Z 323					
Serial numbe	r	H2932-002-	50430				
Test condition	ns						
I HV	10	DIN EN ISC	6507-1.201	8-07			
HBW		DIN EN ISC					
HRC	and the second second	DIN EN ISC					
	dia constant lines	mperatur, if o	and the second				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	Parts result of Assarding		
Indentation	d,	dz	dm	Hardness HV	Mean value HV	Distance in mm	Remark
no.	μm	μm	mm	nv	н	mai	
1	323,2	324,7	0,3240	177	-		7
2	326,8	326,8	0,3268	174	172		
3	331,4	328,6	0,3300	170			BM 1
4	333,9	327,8	0,3309	169			
5	331,9 365,0	332,4 327,0	0,3321 0,3460	168 155			
2	297,9	303,3	0,3460	205			
3	292,1	298,2	0,2951	213	198		HAZ 1
4	295,4	293,1	0,2942	214			
5	301,0	304,1	0,3025	203			
1	315,6	320,1	0,3178	184			
2	323,2 311,0	315,3 306,9	0,3192 0,3089	182 194	185	-	WM
4	327,8	316,1	0,3089	179	105		• • • • •
5	315,8	313,3	0,3145	187			
1	304,1	301,0	0,3025	203			
2	300,2	298,2	0,2992	207			
3	294,4	294,9	0,2946	214	210	<u>(</u>	HAZ 2
4	294,9 294,1	299,5 294,9	0,2972 0,2945	210 214			
1	330,8	330,8	0,2343	169			
2	327,8	328,0	0,3279	172			
3	322,4	322,2	0,3223	179	176		BM 2
4	322,4	323,2	0,3228	178			
5	320,4	321,2	0,3208	180			
		1					
Date:	06.11.22						
Tester:	Scheck						
icater.	Scheck						

Figure 3.50: Hardness measurements of 14HGS (7)

\mathbb{N}	STUTTG		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	21 UN (1);	Root				
Administrato		Silcher					2 Margaretters of
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ns						
	10	DIN EN ISO	6507 1-201	9.07			
DATE IN ADDRESS	10						
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou	tside (23+/-	5) *C			
Control	280,6	280,8	0,281	235		References	237 HV 10
plate	μm	μm	mm	HV		neierence.	237 HV 10
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Activity
	226.0	205 F	0.0057	475			
1	326,0 331,1	325,5 330,8	0,3257 0,3310	175 169	4 - 1		
3	329,1	332,9	0,3310	169	169		
4	332,6	336,0	0,3343	166			BM 1
5	333,9	334,4	0,3342	166			
1	317,3	319,4	0,3183	183			
2	313,0	313,2	0,3131	189	1 [HAZ 1
3	307,4	312,0	0,3097	193	189	=	
4	311,7	311,2	0,3115	191			
5	313,2	313,2	0,3132	189			
1	330,6	333,9	0,3323	168			
2	329,8	331,9	0,3308	169	169		WМ
3	333,1 329,6	332,6 329,8	0,3329 0,3297	167 171	109		VVIVI
4	329,6	329,8	0,3297	168	1 1		
1	307,9	308,7	0,3083	195			
2	308,1	308,7	0,3084	195	1 1		
3	306,1	307,6	0,3069	197	201		HAZ 2
4	305,1	301,8	0,3034	201			
5	290,5	294,9	0,2927	216			
1	339,3	336,2	0,3377	163			
2	333,4	335,2	0,3343	166			
3	330,3	331,9	0,3311	169	169		BM 2
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)

\mathbb{N}		ART	M	Test rej PAS-PPB 523 Hardness	310-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	iption	21 UN (1), C	Outer laver				
Administrato	or	Silcher				PU AL. MA	
Test instrum							
		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ns						
I HV	10	DIN EN ISO	6507-1.201	8-07		The second	
□ HBW		DIN EN ISO					
HRC		DIN EN ISO	6508-1:201	6-12			
	Test ten	nperatur, if o	utside (23+	45) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV		increase incer	237 114 10
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	2010/06/06/2
1	311,3	314,9	0,3131	189		-	-
2	311,8	314,9	0,3151	186	185		
3	311,8	314,9	0,3133	189			BM 1
4	316,3	319,2	0,3178	184			
5	321,5	322,1	0,3218	179			
1	329,4	329,8	0,3296	171		-	
2	306,0	308,9	0,3074	196	100		
3 4	294,7 298,9	302,0 294,5	0,2984 0,2967	208 211	198		HAZ 1
4	302,4	294,5	0,2967	205			
1	319,2	320,9	0,3201	181			1
2	324,0	324,4	0,3242	176			1
3	316,3	320,3	0,3183	183	179		WM
4	321,5	311,3	0,3164	185	19 43 - CT / T 1]
5	330,2	327,9	0,3291	171			
1	298,5	295,8	0,2971	210			
2	303,9	303,5	0,3037	201	205		HAZ 2
3	297,6 305,1	296,0 307,2	0,2968 0,3062	210 198	205		
4	298,7	298,3	0,3082	208			1
1	332,3	332,1	0,3322	168			
2	330,2	331,7	0,3310	169			1
3	324,0	324,6	0,3243	176	174		BM 2
4	319,5	326,9	0,3232	178			
5	325,1	321,1	0,3231	178		-	
	06.11.22 Scheck	1	I		L		<u> </u>

Figure 3.52: Hardness measurements of 14HGS (9)

\mathbb{N}	STUTTG		MP	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	21 UN (1);	Root				
Administrato	r	Silcher					
Test instrum	101		(
		Zwick Z 323					
Serial numbe	r	H2932-002-	50430				
Test conditio	ns						
⊡ HV ·	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC	Test		6508-1:201				
	A CHORNEL DAGES	peratur, if ou	Support Dates of A			- 1.P	Tour care and the
Control plate	280,6	280,8	0,281	235 HV		Reference:	237 HV 10
	μm d1	μm	mm		Manu series	Distance in	
Indentation no.	a, µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
		Part					
1	318,2	318,2	0,3182	183			
2	327,3	326,9	0,3271	173	100000000000000000000000000000000000000		
3	335,8	332,9	0,3344	166	168		BM 1
4	342,3	343,3	0,3428	158			
5	339,6 335,2	341,2 337,7	0,3404 0,3365	160 164			
2	331,5	328,6	0,3305	170			
3	325,9	326,9	0,3264	174	172		HAZ 1
4	321,3	319,0	0,3202	181			
5	326,7	327,5	0,3271	173			
1	339,6	335,4	0,3375	163			
2	337,5	336,7	0,3371	163			
3	332,5	335,2	0,3339	166	162		WM
4	337,9	339,2	0,3385	162			
5	343,9	345,0	0,3444	156			
1	328,8 328,6	324,8 328,8	0,3268 0,3287	174 172			
3	332,1	328,8	0,3207	172	168		HAZ 2
4	337,1	334,8	0,3359	164			
5	340,8	336,9	0,3389	161			
1	337,7	330,9	0,3343	166			
2	327,1	331,3	0,3292	171	and a second state		
3	328,2	324,6	0,3264	174	174		BM 2
4	323,4	321,7	0,3226	178			
5	319,4	325,3	0,3224	178			
	06.11.22 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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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_{JIc} [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

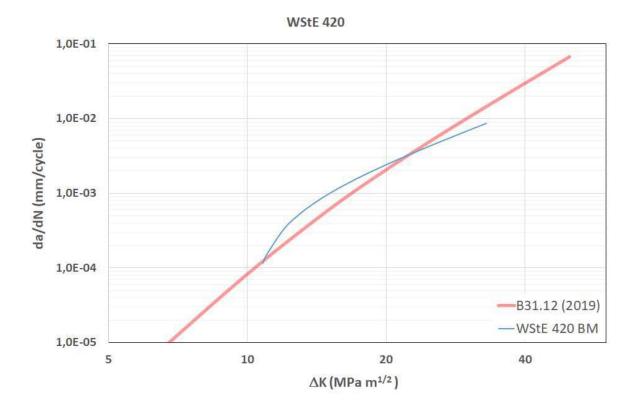


Figure 3.54: Crack growth WStE 420

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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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.

- base material
- girth weld

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

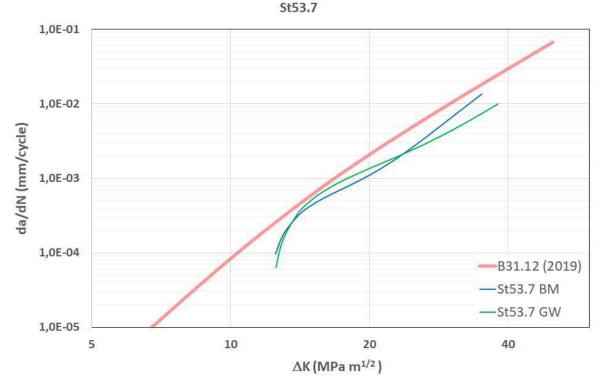


Figure 3.55: Crack growth St53.7

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.

\mathbb{N}			Test report MPAS-PPB 52310-08/1 Hardness test			Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	19.1; Outer	layer				
Administrato		Silcher	Sector Control In				
			2				Last and a
Test instrume		Zwick Z 323	(neu)				
Serial numbe	r	H2932-002-	50430				
Test condition	ns						
	10	DIN EN ISC	6507-1:201	8-07			
DAL THE REAL PROPERTY.							
HBW			6506-1:201	0.65 (1.2020)			
HRC		DIN EN ISC	6508-1:201	6-12			
	Test ten	nperatur, if o	utside (23+	45) *C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		increased.	237 11 10
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	10101020022
1	310,5	309,7	0,3101	102			
2	318,0	315,3	0,3166	193 185	4 - 1		
3	319,0	317,2	0,3181	183	185	-	
4	315,7	318,8	0,3173	184			BM 1
5	321,1	324,2	0,3227	178			
1	284,8	288,3	0,2865	226			
2	287,9	289,3	0,2886	223	000		
3	284,8 292,7	284,8 292,3	0,2848 0,2925	229 217	223		HAZ 1
4	292,7	292,3	0,2925	217			
5	309,3	304,5	0,2904	197		1	
2	303,9	301,8	0,3028	202			
3	312,2	307,6	0,3099	193	192		WM
4	312,6	311,1	0,3119	191]
5	322,8	321,5	0,3221	179			
1	301,4	302,6	0,3020	203			
2	287,5	286,9	0,2872	225	220		
3	287,1 283,1	288,9 283,5	0,2880 0,2833	224 231	220	-	HAZ 2
4	292,5	283,5	0,2833	231			
1	321,5	322,3	0,2312	179		1	
2	316,9	323,6	0,3203	181			
3	315,3	319,9	0,3176	184	181		BM 2
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)

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallog	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)						
Sample descr	iption	19.1; Root	t	and the second					
Administrato	r	Silcher							
Test instrum									
		Zwick Z 323	(neu)	12 52 52					
Serial numbe	er	H2932-002-	50430						
Test conditio	ns								
⊡ HV ·	10	DIN EN ISC	6507-1-201	8-07					
B HBW									
		DIN EN ISC							
HRC		DIN EN ISC							
	Test tem	peratur, if ou	tside (23+/-	5) *C					
Control	280,6	280,8	0,281	235		Reference:	237 HV 40		
plate	μm	μm	mm	HV		nererence.	237 11 10		
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	2010/07/02		
1	320,9	318,4	0,3196	181					
2	318,8	321,9	0,3130	181	4 - F				
3	320,7	323,4	0,3220	179	179		BM 1		
4	321,5	325,0	0,3233	177] [
5	324,4	323,6	0,3240	177					
1	334,8	337,7	0,3363	164					
2	327,9	323,0	0,3255	175	171				
3 4	330,6 330,0	327,3 328,2	0,3290 0,3291	171 171			HAZ 1		
5	327,9	326,2	0,3291	173	4 }				
1	315,1	312,8	0,3139	188					
2	319,0	316,5	0,3178	184	1 1				
3	325,7	321,5	0,3236	177	180		WM		
4	324,0	323,2	0,3236	177	1 1				
5	329,2	327,9	0,3286	172					
1	329,4	329,2	0,3293	171					
2	321,1	320,3	0,3207	180	100				
3	315,7	314,5	0,3151	187	183		HAZ 2		
4	317,0 311,8	312,8 309,5	0,3149 0,3106	187 192	4 }				
D 1	323,8	309,5	0,3106	192					
2	323,2	328,2	0,3244	175	1 1				
3	323,2	325,0	0,3241	177	177		BM 2		
4	319,6	325,5	0,3226	178	1 1				
5	313,8	327,9	0,3209	180					
Date:	06.11.22								
Tester:									
	Scheck								

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

\mathbb{N}			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie			
Order numb	er	9039784000	1						
Sample descr	iption	19.2; Outer	layer			- All - water			
Administrato	r	Silcher	211.4 MID	•					
						and the second			
Test instrum		Zwick Z 323	(neu)						
Serial numbe	er -	H2932-002-	50430						
Test conditio	ns					1			
⊡ HV ·	10	DIN EN ISO	6507-1.201	8-07		100			
B HBW									
		DIN EN ISO							
HRC		DIN EN ISO	6508-1:201	6-12					
	Test tem	peratur, if ou	tside (23+/-	5) *C					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10		
plate	μm	μm	mm	HV			257 110 10		
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	2010/02/2010		
1	312,0	314,7	0,3133	189					
2	311,8	317,8	0,3133	187	4 F				
3	313,8	319,0	0,3164	185	185		BM 1		
4	318,2	318,8	0,3185	183					
5	320,7	320,1	0,3204 0,3178	181 184					
2	317,8 302,2	317,8 305,3	0,3178	201		-	HAZ 1		
3	307,2	307,6	0,3074	196	192				
4	311,3	310,5	0,3109	192	1000 M (2000)	-			
5	314,9	314,7	0,3148	187					
1	321,1	322,8	0,3219	179					
2	322,1 340,0	320,7 332,7	0,3214 0,3364	180 164	178		WM		
4	317,6	316,5	0,3304	184	170				
5	317,6	315,9	0,3167	185					
1	296,2	296,2	0,2962	211					
2	294,8	294,9	0,2948	213			HAZ 2		
3	294,7	295,4	0,2951	213	210				
4	300,8 298,7	298,5 299,3	0,2996	207 207					
1	320,9	329,4	0,3252	175					
2	313,4	320,7	0,3171	184					
3	312,6	318,2	0,3154	186	185		BM 2		
4	309,7	316,1	0,3129	189					
5	308,0	313,2	0,3106	192			-		
120-200									
Date:	06.11.22								
Tester:	Scheck								
	- all a off								

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

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)					
Sample descr	iption	19.2; Root	ot					
Administrato		Silcher						
			a					
Test instrum	ent	Zwick Z 323	(neu)					
Serial numbe	r	H2932-002-	50430					
Test conditio	ns							
⊡ HV ·	10	DIN EN ISO	6507-1.201	8-07		a state		
Phil I I I Andrew					and the second second			
HBW		DIN EN ISO		508 329895				
HRC		DIN EN ISO	6508-1:201	6-12				
	Test tem	peratur, if ou	itside (23+/-	-5) *C				
Control	280,6	280,8	0,281	235		References	237 HV 10	
plate	μm	μm	mm	HV		nererence.	237 HV 10	
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	1010102-002	
	319,0	321,1	0,3201	181				
2	319,0	321,1	0,3201	181			1	
3	322,4	320,7	0,3215	179	180		BM 1	
4	317,8	320,1	0,3189	182	1. S.			
5	325,2	326,5	0,3259	175				
1	315,3	312,4	0,3138	188				
2	312,4	311,3	0,3119	191	There are a large			
3	316,1	312,8	0,3145	188	188		HAZ 1	
4	314,3	313,8	0,3140	188	1 1			
5	315,9	318,0	0,3169	185				
1	306,6	303,5 297,4	0,3050	199			4	
2	303,7 296,2	297,4	0,3006	205 215	280		l wм	
4	230,2	216,9	0,2934	388	200			
5	217,0	210,3	0,2175	392			1	
1	312,8	314,9	0,3138	188				
2	313,6	308,0	0,3108	192	1		1	
3	303,9	305,5	0,3047	200	198		HAZ 2	
4	299,3	297,2	0,2983	208	. I		1	
5	304,3	302,2	0,3033	202				
1	312,4	316,1	0,3143	188			1	
2	314,2	317,8	0,3160	186	100			
3	305,3	313,4	0,3094	194	192		BM 2	
4	302,2 308,2	304,9 312,2	0,3036 0,3102	201 193			1	
5	500,2	512,2	0,0102	105				
	06.11.22 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

Ob anni a al a anna a siti a n	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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 _{Jlc} [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.

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

 $^{^{\}rm 12}$ Notched-bar impact test as per Charpy (EN ISO 148-1) at 0 $^{\circ}{\rm C}$

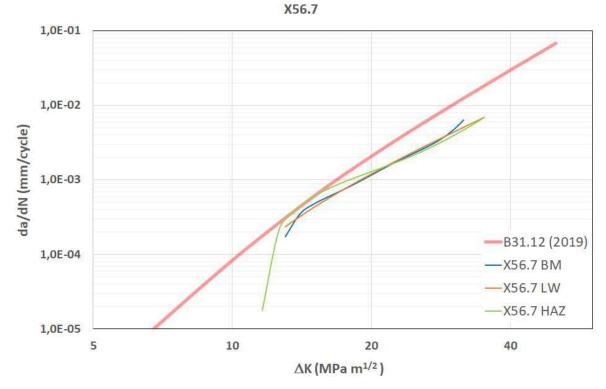


Figure 3.60: Crack growth X56.7

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.

\mathbb{N}	STUTTG		MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	12.1-LN Ou	ter layer				
Administrato	r	Silcher			Constant State		Contraction in the stand
Test instrume			(nou)				
	111120	Zwick Z 323	TUNE DUN Anarta Startan				
Serial numbe	r	H2932-002-	50430				
Test condition	ns						
I HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1.201	5-02			
				N_			
HRC	1000 States	DIN EN ISO					
	A CONTRACTOR	peratur, if ou	Successive sectores				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	122,1531047024101		
Indentation	d,	dz	dm	Hardness HV	Mean value HV	Distance in	Remark
no.	μm	μm	mm	nv	HV	mm	
1	296,2	293,1	0,2946	214			
2	293,1	292,9	0,2930	216	1 1		
3	288,5	288,9	0,2887	222	218		BM 1
4	288,8	292,1	0,2904	220			
5	292,7 272,7	292,2 270,9	0,2925	217 251			
2	275,3	274,6	0,2749	245			
3	268,8	269,2	0,2690	256	246	-	HAZ 1
4	279,8	277,5	0,2786	239			
5	280,2	276,3	0,2782	240			
1	275,6	273,8 278,8	0,2747	246 240			
2	277,3 279,4	278,8	0,2780	240	240		WM
4	279,0	275,4	0,2000	241	240		
5	279,8	280,4	0,2801	236			
1	268,6	267,1	0,2679	258			
2	270,5	273,6	0,2720	251	050		
3	273,8 270,2	273,6 275,0	0,2737 0,2726	248 249	250		HAZ 2
5	270,2	275,0	0,2726	249			
1	292,9	294,1	0,2935	215			
2	294,8	296,2	0,2955	212			
3	291,6	293,5	0,2926	217	213		BM 2
4	295,4	296,6	0,2960	212			
5	299,9	297,2	0,2986	208			
Date: (06.11.22				<u>I</u>	<u> </u>	
Tester:	Scheck						

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

\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	12.1-LN Ce	nter				
Administrato	r	Silcher				Carlos Sal	
Test instrume	ant	Zwick Z 323	(nou)				
Serial numbe		H2932-002-					
		H2932-002-	50430			A Mine wind the	
Test condition	ns						
I HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test ten	nperatur, if o					
Control	280,6	280,8	0,281	235		Defer	
plate	μm	μm	mm	HV		Kererence:	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Action
1	314,7	316,7	0.3157	186			
2	314,7	319,0	0,3157	184			
3	312,0	311,5	0,3118	191	191		BM 1
4	304,9	305,1	0,3050	199			
5	308,6	307,2	0,3079	196			
1	284,1	283,5	0,2838	230			
2	282,7	279,6	0,2811	235			HAZ 1
3	285,4	283,9	0,2847	229	223		
4	287,7 302,6	289,1 305,5	0,2884	223 201			
5	292,2	287,5	0,3041	201			
2	293,1	290,6	0,2033	218			
3	296,4	296,4	0,2964	210	214		WM
4	298,3	293,5	0,2959	212	1999		1
5	298,9	300,1	0,2995	207			1
1	276,3	279,2	0,2777	240			
2	277,9	277,1	0,2775	241			HAZ 2
3	274,8	276,7	0,2758	244	231	-	
4	288,3 300,6	290,8 297,4	0,2895	221 207			4
1	317,8	319,4	0,2990	183	P		
2	313,8	312,8	0,3133	189			
3	314,3	314,2	0,3143	188	188		BM 2
4	314,7	312,6	0,3136	189]
5	312,2	314,0	0,3131	189			
- <u>19</u> 05-000 - 10							
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}	STUTTGA	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	12.1-LN R	oot			-	
Administrato	r	Silcher				Sec. A.	
			()				
Test instrume		Zwick Z 323	al de la companya de La companya de la comp			CARS /	
Serial numbe	r	H2932-002-	50430				
Test condition	ns						
⊡ HV 1	10	DIN EN ISC	6507-1.201	8-07			
No. Company							
HBW			6506-1:201	No. and			
HRC			6508-1:201				
	Test ten	nperatur, if o	utside (23+	45) *C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		nererence.	237 HV 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	A COMPANY
	205.0	200.4	0.0074	24.0			
1	295,8 293,7	299,1 298,3	0,2974 0,2960	210 212			
3	291,6	297,2	0,2944	212	212		BM 1
4	292,0	297,6	0,2948	213			DIVI I
5	292,9	301,6	0,2972	210			
1	304,9	305,5	0,3052	199			
2	293,9	294,9	0,2944	214			
3	291,2	292,2	0,2917	218	220		HAZ 1
4	285,2	284,8	0,2850	228			
5	276,5 287,9	278,4 287,3	0,2774 0,2876	241 224			
2	286,2	287,3	0,2870	224			
3	283,9	280,0	0,2820	233	228		WМ
4	286,2	284,2	0,2852	228			
5	283,3	285,0	0,2842	230			
1	295,6	296,8	0,2962	211			
2	287,9	289,8	0,2888	222			
3	286,2	287,5	0,2869	225	224		HAZ 2
4	285,2	284,6	0,2849	228			
5	282,9 299,7	281,5 302,4	0,2822 0,3011	233 205			
2	293,5	298,9	0,2962	203			
3	292,5	296,2	0,2943	214	209		BM 2
4	296,8	297,4	0,2971	210			
5	298,3	305,1	0,3017	204			
	_						
Date:	06.11.22						
	Scheck						

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

\mathbb{N}	STUTTG,	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	12.2-LN Ou	ter layer				Ultra
Administrato	r	Silcher					
Test instrum			()			No. Contraction	
		Zwick Z 323					
Serial numbe	r	H2932-002-	50430			America	
Test conditio	ns						
I HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO					
				Sector 1			
HRC	The second second	DIN EN ISO					
	Test ten	peratur, if ou	itside (23+/	-5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	, solution data
1	302,8	296,8	0,2998	206			
2	297,6	298,1	0,2938	200			1
3	299,7	295,6	0,2976	209	210		BM 1
4	297,5	294,1	0,2958	212			
5	294,7	294,9	0,2948	213			
1	281,0	277,5	0,2793	238			
2	282,9	274,2	0,2786	239			
3	276,9	278,1	0,2775	241	237		HAZ 1
4	282,9	281,3	0,2821	233			
5	281,7 282,1	279,6 280,8	0,2806	235 234		0000000000000000	
2	285,8	280,8	0,2815	234		1	
3	286,6	284,4	0,2855	227	231		WM
4	282,3	282,7	0,2825	232	,	1	
5	285,2	282,7	0,2840	230			1
1	289,8	292,2	0,2910	219			
2	280,8	277,3	0,2791	238]
3	283,1	278,5	0,2808	235	233		HAZ 2
4	280,0	282,1	0,2810	235			4
5	280,6	277,1	0,2789	238			
1	304,1 298,9	304,1 297,4	0,3041 0,2982	201 209			•
3	302,2	300,5	0,2982	203	204	0	
4	301,4	301,0	0,3012	204	234		BM 2
5	302,0	302,4	0,3022	203			
	06.11.22 Scheck						

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

\mathbb{N}	STUTTGA		MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000	Ē				
Sample descr	ription	12.2-LN Ce	nter			-	
Administrato	or	Silcher					
						No. CON	
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430			1 March 19	
Test conditio	ns				man and a second		
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO					
HRC		DIN EN ISO					
	Test tem	peratur, if ou	tside (23+/-	-5) °C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		nererence.	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	10101010-0152
1	315,1	317,8	0,3164	185			1
2	318,4	314,9	0,3166	185			
3	313,2	311,1	0,3122	190	188		BM 1
4	313,0	312,6	0,3128	190] [
5	311,3	309,5	0,3104	192			
1	282,1	279,6	0,2808	235			
2	284,8 288,9	285,4 287,9	0,2851 0,2884	228 223	215		
4	307,2	305,1	0,2004	198	215		HAZ 1
5	308,6	310,3	0,3095	194			
1	288,3	286,6	0,2875	224	-		
2	290,6	288,3	0,2895	221		-	1
3	292,5	287,9	0,2902	220	214		WM
4	302,6	299,7	0,3012	204			
5	302,6	304,1	0,3034	202			
1	285,6	283,3	0,2845	229			
2	285,0 286,4	285,8 285,6	0,2854 0,2860	228 227	220		HAZ 2
4	298,9	205,0	0,2860	209	220		
5	300,1	299,3	0,2997	206			1
1	320,7	321,1	0,3209	180			
2	318,8	316,5	0,3177	184			
3	315,5	312,6	0,3140	188	187		BM 2
4	309,3	309,3	0,3093	194			
5	313,8	312,8	0,3133	189			
	06.11.22 Scheck						

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

\mathbb{N}	STUTTGA		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample descr	iption	12.2-LN R	oot				
Administrato		Silcher				Section 2.	
Seator I MANAGEMETER	101		(mar)				
Test instrum		Zwick Z 323					
Serial numbe	r	H2932-002-	50430			Brace aller	
Test conditio	ns				Street opening the second		Contraction Contract
I HV ·	10	DIN EN ISC	6507-1:201	8-07			
HBW			6506-1:201				
HRC			6508-1:201				
	Test tem	peratur, if ou	itside (23+/-	-5) °C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		increased.	23/ 110 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	2010/02/09/002
1	301,6	300,5	0,3011	205			
2	302,0	303,9	0,3029	202	1 1		
3	296,4	300,8	0,2986	208	206		BM 1
4	297,6	302,6	0,3001	206	1 [2
5	297,2	300,6	0,2989	208			
1	289,1	286,2	0,2877	224	4 1		
2	286,4 294,9	289,8 292,9	0,2881 0,2939	223 215	215		
4	294,9	292,9	0,2935	213	215		HAZ 1
5	304,5	302,8	0,3037	201	1 1		
1	300,1	302,4	0,3013	204			
2	302,2	302,8	0,3025	203	1 1		
3	300,1	299,9	0,3000	206	202		WM
4	308,2	306,4	0,3073	196	1 1		
5	304,9	304,1	0,3045	200			
1	307,6 299,3	306,4 295,6	0,3070 0,2974	197 210	4		
3	299,3	295,0	0,2974	209	209		HAZ 2
4	294,5	292,9	0,2973	215	200		
5	293,9	291,6	0,2928	216		_	
1	310,3	310,7	0,3105	192			
2	304,1	307,4	0,3057	198			
3	300,8	302,2	0,3015	204	201		BM 2
4	299,3 298,5	301,8 301,4	0,3006 0,2999	205 206			
5	200,0	301,4	0,2399	200			r
	06.11.22 Scheck						

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

\mathbb{N}	STUTTGA	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	12.1-UN OL	iter layer				
Administrato	r	Silcher					
Test instrume		Zwick Z 323	(nou)				and the
			Contraction of the Contraction				
Serial numbe	r	H2932-002-	50430		-		
Test condition	ns						
I HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1.201	5-02			
HRC		DIN EN ISO					
	and the second street of	peratur, if ou	STOCKET DAMAGE OFFIC				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	Constant of the second s		
Indentation	d,	d ₂	d _m	Hardness HV	Mean value HV	Distance in	Remark
no.	μm	μm	mm	nv	HV	mm	
1	305,3	308,4	0,3069	197		(
2	305,7	308,6	0,3072	197			
3	304,7	305,1	0,3049	199	197		BM 1
4	306,4	310,1	0,3082	195			
5	305,7 296,4	309,7 295,8	0,3077	196 212			
2	296,4	295,8	0,2961	212	4 1		
3	284,0	292,0	0,2880	224	221	1	HAZ 1
4	287,6	285,8	0,2867	226			
5	294,3	294,2	0,2943	214			5
1	308,0	303,0	0,3055	199			-
2	305,9	304,7	0,3053	199			
3	314,5	315,7	0,3151	187	188		WM
4	314,1	314,7	0,3144	188			
5	332,3	331,5	0,3319	168			
1	291,0	287,7	0,2894 0,2890	221 222		[
2	286,6 286,9	291,4 287,7	0,2890	222	222		HAZ 2
4	290,6	291,6	0,2073	219	222	1	
5	289,6	287,3	0,2884	223			
1	304,3	312,6	0,3084	195			
2	306,3	314,5	0,3104	192			
3	303,7	312,6	0,3081	195	196		BM 2
4	304,1	306,8	0,3054	199			
5	302,0	310,3	0,3062	198			-
	06.11.22 Scheck						

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

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numbe	er	9039784000)				
Sample descr	iption	12.1-UN F	loot				
Administrato	r	Silcher					
Test instrum		Zwick Z 323	(
			100 X 302102080	Taria			
Serial numbe	r	H2932-002-	50430		5		
Test conditio	ns					1	and the second second
U HV ·	10	DIN EN ISC	6507-1:201	8-07			
HBW		DIN EN ISC	6506-1:201	5-02			
HRC			6508-1:201				
	Test tors	DIN EN ISC peratur, if out					
	A Geodesian Disease	Carbon Construction of the local	apose in exectory			1.110.0	
Control plate	280,6	280,8	0,281	235 HV		Reference:	237 HV 10
Indentation	μm d1	µm d ₂	mm d _m	Lational Contraction of the	Mean value	Distance in	
no.	μm	μm	mm	Hardness HV	HV	mm	Remark
1	303,9	309,5	0,3067	197			
2	303,7	307,6	0,3056	199 196	194		BM 1
3 4	305,1 309,1	310,1 312,2	0,3076 0,3106	196	194		
5	313,6	317,6	0,3156	186			
1	317,4	316,3	0,3169	185			
2	318,4	319,0	0,3187	183			
3	324,2	323,2	0,3237	177	179		HAZ 1
4	322,3	323,6	0,3230	178			
5 1	328,2 313,4	331,1 311,3	0,3296	171 190	I		
2	315,3	312,8	0,3124	188			
3	326,5	326,1	0,3263	174	180		WM
4	320,1	317,6	0,3188	182			
5	337,3	334,8	0,3360	164			
1	335,4	340,2	0,3378	163 176			
2	322,3 313,6	326,3 323,0	0,3243 0,3183	176	174		HAZ 2
4	322,1	329,6	0,3259	175			
5	320,5	330,0	0,3252	175			
1	316,3	324,4	0,3204	181			
2	314,2	322,6	0,3184	183	464		
3	314,5	323,4	0,3189	182 184	184		BM 2
4	314,0 308,4	320,3 319,7	0,3172 0,3140	184			
			-,				
Date:	06.11.22						
Tester:	Scheck						

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

Order number ample descrip Administrator Fest instrumer Serial number Fest condition Test condition HV 10 HBW HRC	ption nt s	9039784000 12.2-UN Ou Silcher Zwick Z 323 H2932-002- DIN EN ISO DIN EN ISO DIN EN ISO	(neu) 50430 6507-1:201 6506-1:201 6508-1:201	5-02							
Administrator Fest instrumen Serial number Fest condition HV 10 HBW	nt s) Test tem	Silcher Zwick Z 323 H2932-002- DIN EN ISO DIN EN ISO DIN EN ISO	(neu) 50430 6507-1:201 6506-1:201 6508-1:201	5-02							
Fest instrumen Serial number Fest condition THV 10 HBW	nt s) Test tem	Silcher Zwick Z 323 H2932-002- DIN EN ISO DIN EN ISO DIN EN ISO	(neu) 50430 6507-1:201 6506-1:201 6508-1:201	5-02							
Fest instrumen Serial number Fest condition THV 10 HBW	nt s) Test tem	Zwick Z 323 H2932-002- DIN EN ISO DIN EN ISO DIN EN ISO	50430 6507-1:201 6506-1:201 6508-1:201	5-02							
Serial number Fest conditions I HV 10 HBW	s) Test tem	H2932-002- DIN EN ISO DIN EN ISO DIN EN ISO	50430 6507-1:201 6506-1:201 6508-1:201	5-02							
rest condition I HV 10 HBW	s) Test tem	din en Iso din en Iso din en Iso	6507-1:201 6506-1:201 6508-1:201	5-02							
⊡ HV 10 ⊡ HBW) Test tem	din en Iso Din en Iso	6506-1:201 6508-1:201	5-02							
нвw	Test tem	din en Iso Din en Iso	6506-1:201 6508-1:201	5-02							
	page scalinger	DIN EN ISO	6508-1:201			and the second second					
	page scalinger	DIN EN ISO	6508-1:201		0 6506-1:2015-02						
	page scalinger			6 12							
	page scalinger	peratur, not	itside /22+1								
Control	200,0	280,8	0,281	235		1994	Descensor-ND.				
plate	μm	μm	0,201 mm	HV		Reference:	237 HV 10				
ndentation	d,	d ₂	dm	Hardness	Mean value	Distance in					
10.	μm	μm	mm	HV	HV	mm	Remark				
1	313,0	319,3	0,3161 0,3119	186 191		-					
2	310,1 305,7	313,6 309,7	0,3119	191	192		BM 1				
4	305,5	313,8	0,3097	193							
5	308,0	310,5	0,3093	194							
1	291,4	293,3	0,2924	217							
2	285,8 284,4	286,2 286,4	0,2860 0,2854	227 228	226						
4	280,6	286,9	0,2834	220	220		HAZ 1				
5	284,4	284,6	0,2845	229							
1	315,7	320,3	0,3180	183							
2	316,5	312,6	0,3146	187							
3	310,1	300,5	0,3053	199	190		WM				
4	312,2 316,5	307,8 313,2	0,3100 0,3149	193 187			1				
1	300,5	297,8	0,2992	207							
2	289,3	288,1	0,2887	222]				
3	281,9	281,7	0,2818	234	218		HAZ 2				
4	290,4	288,3	0,2893	222			4				
5	299,3 315,1	299,1 316,3	0,2992 0,3157	207 186							
2	312,8	316,7	0,3148	187			1				
3	310,3	309,9	0,3101	193	191		BM 2				
4	310,1	311,1	0,3106	192			1				
5	304,3	309,3	0,3068	197			-				
202030	1999-012			*******	concernence.	400000000000000000000000000000000000000					
Date: 06	6.11.22										
Tester: S	check										

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

\mathbb{N}	STUTTG	ART Test rep MPAS-PPB 5231 Hardness			10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000	l.				
Sample descr	iption	12.2-UN R	oot				
Administrato	r	Silcher					
Test instrum							
		Zwick Z 323	(neu)				
Serial numbe	r	H2932-002-	50430		and a		
Test conditio	ns						
J HV ·	10	DIN EN ISO	6507-1.201	8-07			
HBW							
		DIN EN ISO		No. of Concession, Name			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou	tside (23+/-	-5) °C			
Control	280,6	280,8 0,281 235			Reference: 237 HV 10		
plate	μm	μm	mm	HV		neierence.	257 11 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
10.	μm	μm	mm	HV	HV	mm	Action
1	315,2	326,3	0,3207	180			
2	309,7 313,2	320,9 316,9	0,3153 0,3151	187 187	187		BM 1
4	306,6	315,1	0,3108	192	107		
5	309,1	316,5	0,3128	190			
1	314,7	318,6	0,3166	185			
2	318,2	314,9	0,3165	185			
3	318,0	316,1	0,3171	184	185		HAZ 1
4	318,0	316,7	0,3174	184			
5	319,0	314,0	0,3165	185			
1	326,9	325,0	0,3260	175			
2	313,4 318,4	314,0 315,3	0,3137 0,3168	188 185	178		WM
4	332,1	315,3	0,3100	169	170		
5	331,3	328,4	0,3298	170		1	
1	320,7	318,8	0,3197	181			
2	320,1	318,8	0,3194	182			
3	320,1	317,8	0,3189	182	182		HAZ 2
4	320,5	320,3	0,3204	181			
5	318,2	318,0	0,3181	183			
1	315,9	319,9	0,3179	184			
2	313,6 311,6	317,4 316,1	0,3155 0,3139	186 188	190		BM 2
4	307,8	312,2	0,3139	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

Ob anni a channa a chian	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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_{JIc} [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.

- base material
- weld material

 $^{^{13}}$ Notched-bar impact testing as per DIN 50115; notch form: DVM; temperature: 0 $^\circ\text{C}$

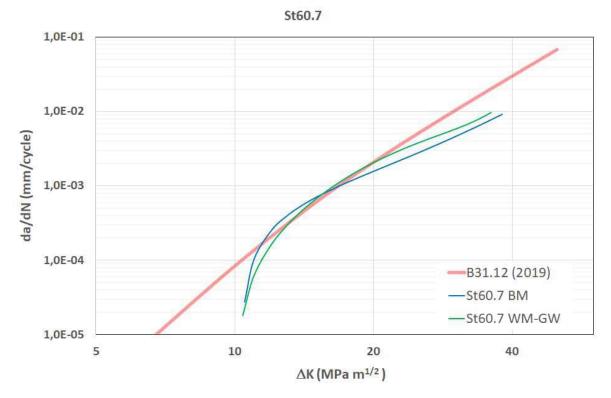


Figure 3.71: Crack growth St60.7

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.

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie				
Order numbe	er	9039784000)								
Sample description		6.1: Outer	6.1: Outer layer								
Administrato											
			Silcher								
Test instrument Serial number		Zwick Z 323 (neu)									
		H2932-002-	50430								
Test condition	ns										
⊡ HV 1	10	DIN EN ISO	6507-1-201	8-07	A STATE OF A						
HBW		COMPOSED NO.									
		DIN EN ISO									
HRC		DIN EN ISO									
	Test tem	peratur, if ou	tside (23+/-	-5) °C							
Control	280,6	280,8	0,281	235		Reference:	227 41 40				
plate	μm	μm	mm	HV		Hereicher	257 114 10				
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark				
no.	μm	μm	mm	HV	HV	mm	2010/00/2010/201				
1	269,2	271,9	0,2706	253							
2	275,0	274,8	0,2749	245							
3	273,6	276,5	0,2750	245	244		BM 1				
4	276,3	277,9	0,2771	242							
5	279,6	279,0	0,2793	238							
1	258,4 249,9	258,8 254,5	0,2586	277 292							
3	249,9	262,7	0,2522	292	279		HAZ 1				
4	251,8	254,0	0,2529	290	210		10021				
5	271,9	272,1	0,2720	251							
1	302,8	305,0	0,3039	201			1				
2	326,3	323,8	0,3250	176	107		wм				
3	320,3	320,1	0,3202	181	187						
4	307,4 323,8	305,1 323,0	0,3063 0,3234	198 177			1				
1	312,2	310,7	0,3114	191							
2	302,0	301,0	0,3015	204							
3	296,8	296,8	0,2968	210	208		HAZ 2				
4	293,1	294,5	0,2938	215							
5	291,2 292,0	288,5 292,5	0,2899 0,2923	221 217							
2	292,0	292,5	0,2923	217							
3	288,5	287,1	0,2878	224	221		BM 2				
4	289,8	288,9	0,2893	221							
5	288,1	292,2	0,2902	220			-				
100000 D											
Date:	06.11.22										
Tester:	Scheck										
	ouncen.										

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

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie					
Order numbe	er	9039784000)								
Sample description		6.1; Root									
Administrato	r	Silcher									
Test instrume		Zwick Z 323 (neu)									
Serial numbe	r	H2932-002-50430									
Test conditio	ns										
⊡ HV ·	10	DIN EN ISC	6507 1.201	8.07	No. of Concession, Name						
Phil I Hansacry											
HBW		DIN EN ISC	6506-1:201	5-02							
HRC		DIN EN ISO	6508-1:201	6-12							
	Test tem	peratur, if ou	tside (23+/-	5) *C							
Control	280,6	280,8	0,281	235		Deference					
plate	μm	μm	mm	HV		Neference:	237 HV 10				
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark				
no.	μm	μm	mm	HV	HV	mm	Nemark				
1	280,0 279,6	286,0 280,0	0,2830 0,2798	232 237	229						
3	279,6	280,0	0,2798	237			BM 1				
4	284,2	290,2	0,2872	225			DIVIT				
5	288,3	294,3	0,2913	219]				
1	304,5	306,8	0,3056	199							
2	301,0	302,6	0,3018	204							
3	302,6 302,0	303,9 302,8	0,3033 0,3024	202 203	201		HAZ 1				
5	305,7	302,8	0,3024	198							
1	316,1	318,0	0,3170	184			-				
2	312,6	310,7	0,3117	191							
3	327,3	327,5	0,3274	173	179		WM				
4	329,2	326,7	0,3279	172							
5	326,9 312,6	328,6 313,4	0,3277 0,3130	173 189							
2	307,6	306,6	0,3130	197	1 1						
3	302,4	299,9	0,3012	204	199		HAZ 2				
4	301,4	302,0	0,3017	204	[
5	305,7	304,7	0,3052	199							
1	294,7 294,7	295,4 294,9	0,2951 0,2948	213 213							
3	294,7	294,9	0,2948	213	216		BM 2				
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)

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie			
Order numb	er	9039784000)						
Sample descr	iption	6.2; Outer	layer		and the second second	A PARTY REPORT	Summer of		
Administrato	r	Silcher							
Test instrum		Zwick Z 323	(neu)						
Serial numbe	r	H2932-002-	50430						
Test conditio	ns								
I HV ·	10	DIN EN ISO	6507-1:201	8-07					
HBW		DIN EN ISO	6506-1:201	5-02					
HRC		DIN EN ISO	6508-1-201	6-12					
	Test tem	peratur, if ou							
Control	280.6	280,8	0,281	235		3250	Descenario e no.		
plate	μm	μm	mm	HV		Reference:	237 HV 10		
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Demark		
10.	μm	μm	mm	HV	HV	mm	Remark		
	070.0	000.4	0.0707	007					
1	279,0 281,2	280,4 283,5	0,2797 0,2824	237 233					
3	280,0	280,4	0,2824	235	233		BM 1		
4	284,0	284,6	0,2843	229					
5	284,0	285,4	0,2847	229			1		
1	252,8	255,5	0,2542	287					
2	241,2	244,1	0,2426	315					
3	252,2	256,4	0,2543	287	267		HAZ 1		
4	275,4	276,7	0,2761	243					
5	305,5	302,0 312,2	0,3038	201 189					
2	313,8 320,9	312,2	0,3130	189			•		
3	312,4	310,3	0,3113	191	189		WM		
4	311,1	309,1	0,3101	193					
5	314,3	312,0	0,3131	189			1		
1	269,0	269,4	0,2692	256					
2	295,1	252,2	0,2736	248					
3	254,7	253,6	0,2542	287	245		HAZ 2		
4	294,5 292,2	290,0 292,5	0,2923	217 217			4		
5	292,2	292,5	0,2923	217					
2	285,6	286,2	0,2859	220		-	1		
3	282,1	285,4	0,2837	230	229		BM 2		
4	278,6	278,3	0,2784	239]		
5	289,8	287,5	0,2886	223					
Date:	06.11.22	1							
Tester:	Scheck								



\mathbb{N}	STUTTG	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie			
Order numbe	er	9039784000)						
Sample descr	iption	6.2; Root					Denne strange		
Administrato		Silcher							
elen in Alesnin, i.e.	51		(mark)						
Test instrum		Zwick Z 323	(neu)						
Serial numbe	r	H2932-002-	50430						
Test conditio	ns								
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07					
HBW			6506-1:201						
HRC			6508-1:201						
	Test ten	nperatur, if o	utside (23+	45) °C					
Control	280,6	280,8 0,281		235		Reference:	237 HV 10		
plate	μm μm mm HV		increased.	257 114 10					
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark		
10,	μm	μm	mm	HV	HV	mm	2010/02/02/02		
1	280,8	284,1	0,2825	232					
2	287,7	288,7	0,2882	223					
3	284,2	292,0	0,2881	223	223		BM 1		
4	288,7	291,6	0,2902	220					
5	291,8	293,1	0,2925	217					
1	287,3	287,3	0,2873	225					
2	292,3	294,1 299,7	0,2932 0,3001	216 206	212				
3	300,6 297,9	299,7	0,3001	206	212		HAZ 1		
5	303,7	302,4	0,2982	203					
1	320,5	318,4	0,3194	182					
2	331,9	329,2	0,3305	170					
3	323,2	322,6	0,3229	178	183		WM		
4	311,3	309,1	0,3102	193					
5	311,1	310,1	0,3106	192					
1	310,7	310,5	0,3106	192					
2	305,1 309,9	305,5 309,3	0,3053 0,3096	199 193	192		HAZ 2		
4	312,6	311,3	0,3098	193	192				
5	314,5	316,1	0,3153	187					
1	292,1	296,6	0,2943	214		-			
2	291,2	292,2	0,2917	218			1		
3	291,0	292,7	0,2918	218	217		BM 2		
4	290,6	295,6	0,2931	216					
5	288,5	292,7	0,2906	220					
And the second s	210222								
Date:	06.11.22								
Tester:	Scheck								
rester:	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	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

Chaminal	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

- base material
- longitudinal weld

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

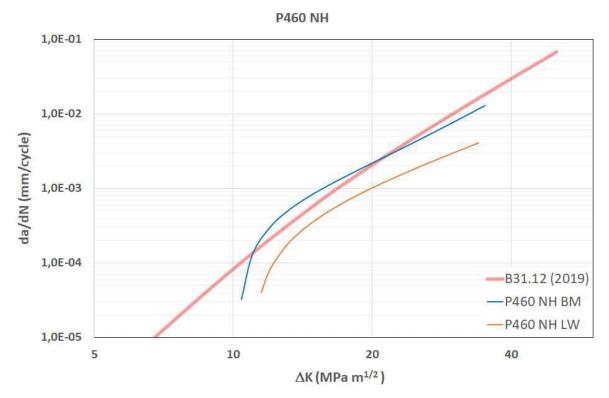


Figure 3.76: Crack growth P460 NH

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.

\mathbb{N}	STUTTG		MF	Test rep AS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie			
Order numbe	er	9039784000)		-				
Sample descr	iption	8.1; Outer	layer			The second state	and the second second		
Administrato		Silcher	2001 - 4-14 D						
Test instrume	51	Zwick Z 323	(nou)						
	-00000-0		11 3						
Serial numbe	r	H2932-002-	50430						
Test condition	ns								
⊡ HV 1	10	DIN EN ISO	6507-1:201	8-07		A starting	New York		
HBW		DIN EN ISO	6506-1.201	5-02					
HRC			6508-1:201						
	Test tem	peratur, if ou	tside (23+/-	5) *C					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10		
plate	μm	μm	mm	HV	Tota segurat a second				
Indentation	d,	d₂	d _m	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	1010304055665		
1	299,9	302,6	0,3013	204					
2	301,0	304,7	0,3028	202					
3	302,2	307,8	0,3050	199	206		BM 1		
4	293,1	298,9	0,2960	212			2		
5	292,5	298,5	0,2955	212					
1	269,4	270,5	0,2699	254					
2	269,2	270,1	0,2696	255	055				
3	270,2 271,9	268,8 268,6	0,2695 0,2703	255 254	255		HAZ 1		
5	268,8	269,4	0,2703	254					
1	278,6	275,2	0,2769	242					
2	281,3	276,7	0,2790	238					
3	275,4	275,2	0,2753	245	242		WM		
4	276,1	275,6	0,2759	244					
5	280,2	276,9	0,2785	239					
1	266,1	266,5	0,2663	261					
2	264,6	267,3	0,2660	262	001				
3	266,9	269,6 269,4	0,2683	258 261	261		HAZ 2		
4	263,6 265,5	269,4	0,2655	261		annanna			
1	310,5	313,8	0,2030	190					
2	307,0	310,5	0,3088	195		<u>.</u>			
3	304,3	309,1	0,3067	197	198		BM 2		
4	300,5	302,6	0,3016	204					
5	299,5	304,1	0,3018	204	[
Date:	06.11.22	1	-		-	-	-		
Tester:	Scheck								

Figure 3.77: Hardness measurements of P460 NH (1)

Order number Sample descrip Administrator Test instrumen Serial number Test conditions	otion	9039784000 8.1; Cente r Silcher Zwick Z 323					
Administrator Test instrumen Serial number		Silcher	ŕ	and the other			and the second second second second
Test instrumen Serial number	nt	W07048746.0-716		the second se			
Test instrumen Serial number	nt	W07048746.0-716			and the second se		
Serial number	11	ZWICK Z 323	(nou)				
		Serial number H2932-002-50430					
rest conditions							
						and shall	No.
HV 10		DIN EN ISO	6507-1:201	8-07		A ANTINIA	a state of the second
HBW		DIN EN ISO	6506-1.201	5-02			N. Contraction
HRC		DIN EN ISO					
	Test tem	peratur, if ou	tside (23+/-	5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			20111110
Indentation	d,	d2	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	204380203056
1	299,9	299,1	0,2995	207		_	
2	299,3	300,2	0,2997	206	1 1		
3	298,7	302,4	0,3006	205	206		BM 1
4	296,6	302,4	0,2995	207			
5	301,2	303,3	0,3022	203			
1	285,0	280,6	0,2828	232		_	
2	292,3	291,4	0,2918	218			· · · · · · · · · · · · · · · · · · ·
3	282,3	283,9	0,2831	231	233		HAZ 1
4	286,9	283,9	0,2854	228	4 4		
5	269,8	268,4	0,2691	256			
1	291,4	289,3	0,2904	220 239	4 4	-	
2	279,4 288,7	277,7 284,2	0,2786 0,2864	239	230		. wm
4	287,9	284,2	0,2861	220	230		V V IVI
5	281,5	279,0	0,2802	236	1 1		
1	274,2	276,7	0,2754	244			
2	308,9	309,3	0,3091	194	1 1		
3	294,1	288,9	0,2915	218	224		HAZ 2
4	303,7	301,6	0,3026	202			
5	267,1	266,9	0,2670	260			
1	301,4	306,4	0,3039	201			
2	297,2	299,9	0,2986	208			
3	302,0	305,9	0,3040	201	202		BM 2
4	301,4 304,9	307,0 306,8	0,3042 0,3058	200 198	4		
ĭ	504,5	000,0	0,0000	100			
	3.11.22 check		.				

Figure 3.78: Hardness measurements of P460 NH (2)

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie			
Order numb	er	9039784000)						
Sample descr	iption	8.1; Root			And				
Administrato		15.							
		Silcher							
Test instrum	ent	Zwick Z 323							
Serial numbe	ial number H2932-002-50430								
Test conditio	ns								
	10		6507-1:201	0.07		A CARA	No. and A		
PER UNIVERSITY	10	realized realized formation				NA STREET	Contraction of the		
HBW		DIN EN ISC							
HRC		DIN EN ISC	6508-1:201	6-12					
	Test tem	peratur, if ou	itside (23+/-	-5) *C					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10		
plate	μm	μm	mm	HV		nererence.	237 HV 10		
Indentation	d,	d₂	dm	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	2010/00/2020		
1	292,9	300,1	0,2965	211					
2	299,1	302,8	0,3010	205					
3	299,7	305,7	0,3027	202	205		BM 1		
4	304,1	306,2	0,3051	199					
5	297,0 261,9	302,0	0,2995	207 272					
2	259,3	260,5 262,4	0,2612	272		7	•		
3	260,9	258,4	0,2597	275	276		HAZ 1		
4	257,4	251,2	0,2543	287					
5	259,0	260,7	0,2599	275					
1	276,3	273,4	0,2748	246					
2	279,8 278,3	276,5	0,2781 0,2772	240 241	242				
3	278,3	276,1 277,3	0,2772	241	242		. WM		
5	273,8	277,3	0,2700	242			1		
1	263,8	265,7	0,2647	265					
2	259,3	263,8	0,2615	271					
3	257,8	258,0	0,2579	279	270		HAZ 2		
4	259,7 264,6	262,1 264,6	0,2609 0,2646	272 265			4		
1	303,5	308,2	0,2040	198					
2	302,8	309,1	0,3060	198			1		
3	300,6	305,3	0,3029	202	198		BM 2		
4	303,9	310,7	0,3073	196			4		
5	305,9	310,3	0,3081	195					
Date:	06.11.22								
Tester:	Scheck								

Figure 3.79: Hardness measurements of P460 NH (3)

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	0-08/1 Metallographie und			
Order numbe	er	9039784000)					
Sample descr	iption	8.2; Outer	layer			The second se		
Administrato		Silcher	Sec. 4 rests					
Test instrume	51		(nou)					
		Zwick Z 323	N. S.					
Serial numbe	r	H2932-002-	50430					
Test condition	ns						A State of the second	
🛛 HV 🔄	10	DIN EN ISO	6507-1:201	8-07	and a second	Charles Int		
DIN EN ISO 6506-1:2015-02							CILCULAR CONTRACT	
HRC		DIN EN ISC						
	Test ten	nperatur, if ou						
Control	280,6	280.8	0,281	235		2302	lastana.	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Bernet	
no.	μm	μm	mm	HV	HV	mm	Remark	
	004.0	000 F	0.0017	040		-		
2	291,0 296,6	292,5 299,7	0,2917 0,2982	218 209				
3	290,2	294,1	0,2921	203	218		BM 1	
4	287,1	291,2	0,2891	222				
5	286,0	289,3	0,2877	224				
1	269,4	269,2	0,2693	256				
2	271,7	269,6	0,2707	253	1000			
3	274,0	271,9	0,2730	249	253		HAZ 1	
4	277,9	267,1	0,2725	250				
5	266,7 279,2	271,3 277,3	0,2690 0,2782	256 240				
2	282,7	277,1	0,2799	240				
3	276,7	275,0	0,2758	244	242		WM	
4	275,0	274,0	0,2745	246				
5	275,2	275,4	0,2753	245				
1	271,5	272,7	0,2721	250				
2	269,2	266,3	0,2678	259				
3	269,2	266,5	0,2679	258	256		HAZ 2	
4	266,7 274,0	263,4 273,8	0,2651 0,2739	264 247				
5	308,9	310,5	0,2739	193				
2	309,5	311,5	0,3105	193				
3	293,1	299,5	0,2963	211	203		BM 2	
4	298,3	305,3	0,3018	204				
5	292,0	297,8	0,2949	213	I			
Contraction for	1993 N. 1990							
Date: (06.11.22							
Tester:	Scheck							
rester:	Scheck							

Figure 3.80: Hardness measurements of P460 NH (4)

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	0-08/1 Metallographie und			
Order numbe	er	9039784000)						
Sample descr	iption	8.2; Root			Same Internet		and the		
Administrato		Silcher					All shares		
Test instrume	ent	Zwick Z 323	(neu)						
Serial numbe	r	H2932-002-	50430						
Test condition	ns								
⊡ HV 1	10	DIN EN ISO	6507-1-201	8-07			A STREET WATCHING		
Ref COLORADON			A		UNISE -				
HBW		DIN EN ISO							
HRC		DIN EN ISO							
	Test ten	nperatur, if ou	utside (23+/	-5) *C					
Control	280,6	280,8	0,281	235		Reference	237 HV 10		
plate	μm	μm	mm	HV		nererence.	237 11 10		
Indentation	d,	d₂	dm	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm			
1	300,1	304,9	0,3025	203					
2	299,7	304,9	0,3025	203					
3	300,1	303,0	0,3016	204	204		BM 1		
4	303,2	305,3	0,3043	200					
5	298,7	300,3	0,2995	207					
1	265,9	269,6	0,2678	259					
2	265,3 260,3	265,5 260,9	0,2654 0,2606	263 273	269		HAZ 1		
4	256,6	256,8	0,2606	273	209	-			
5	263,2	263,6	0,2507	267					
1	284,0	277,5	0,2807	235					
2	279,4	282,5	0,2809	235			1		
3	281,9	279,0	0,2804	236	235		WM		
4	281,7	282,3	0,2820	233					
5	280,2	278,5	0,2794	238					
1	264,2	266,7	0,2655	263					
2	262,0 258,4	266,9 258,8	0,2644 0,2586	265 277	266		HAZ 2		
4	258,4	256,5	0,2560	260	200				
5	263,6	266,5	0,2651	264					
1	294,3	304,5	0,2994	207			-		
2	295,4	304,1	0,2997	206					
3	295,2	299,9	0,2975	209	207		BM 2		
4	294,3	301,6	0,2980	209					
5	301,2	305,1	0,3031	202					
	06.11.22 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	1974 DIN 2470/2 / DIN 17172 / Ruhrgas Standard RN 4205 Re [MPa] 491 Rm [MPa] 598 Kv /A [kgm/cm²] 4 Re [MPa] 517 Rm [MPa] 648			
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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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 _{JIc} [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.

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

 $^{^{15}}$ Transverse notched-bar impact test, sample form DVM, as per DIN 50115, at 0 $^\circ\mathrm{C}$

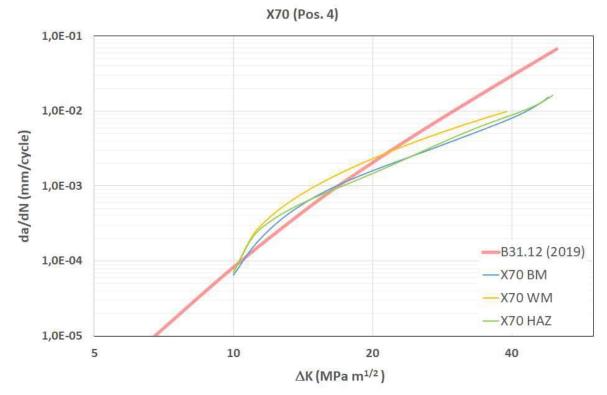


Figure 3.18: Crack growth X70 (item no. 4)

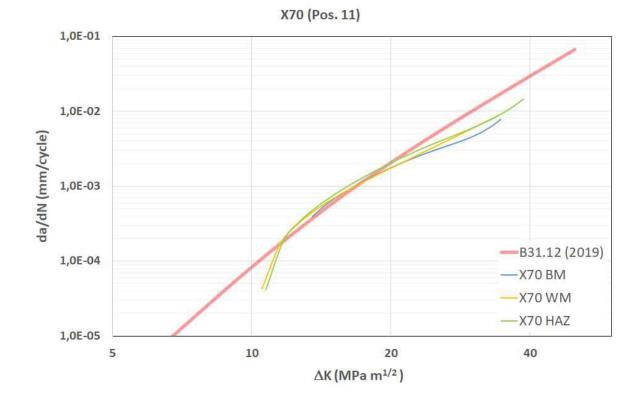


Figure 3.19: Crack growth X70 (item no. 11)

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:

Production year	2017					
Production standards	DIN EN ISO 318	3 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 3.64: Characteristics of L485

Table 3.65: Chemical composition of L485

Chaminal	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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 $^\circ \rm C$

Material	Location	Item no.	K _{JIc} [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

Table 3.66: Fracture toughness of L485

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.

- 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.

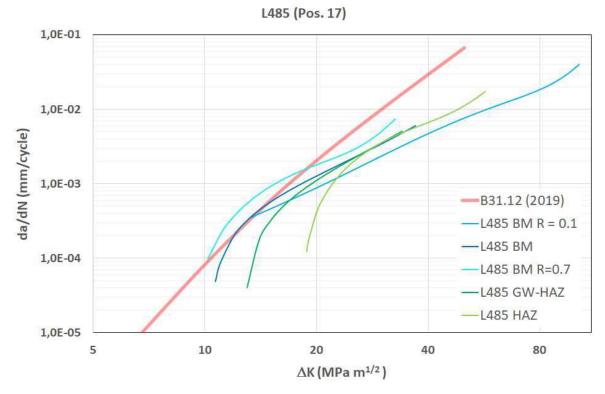


Figure 3.82: Crack growth L485 (item no. 17)

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.

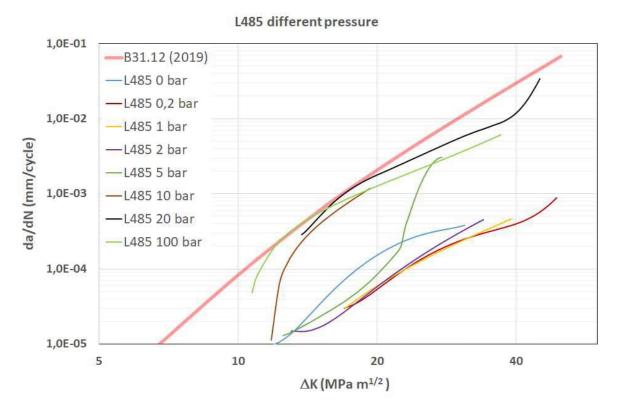
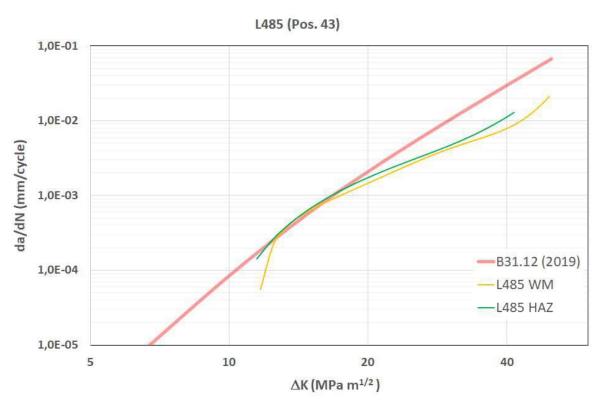


Figure 3.83: Crack growth L485 at different pressures

The curves describing crack growth at item no. 43 (girth weld area tempered to \emptyset 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.

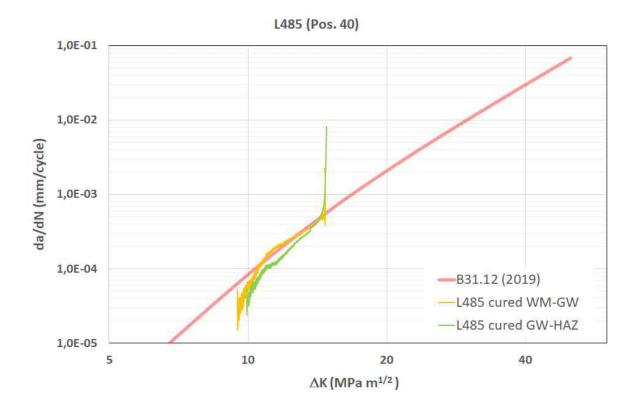


Figure 3.85: Crack growth L485 (hardened)

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.

\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	e ferat graphie und enmikroskopie	
Order numb	er	9039784000)	and the second second	19737		
Sample desc	ription	17.1; Outer	layer		the production		
Administrat	or	Silcher	and the state of			Mar Charles Contraction	
Test instrum		Zwick Z 323				NAL CARACTER	At an and
Serial number	er	H2932-002-	50430			Renard Renards	
Test conditio	ns					and the second second	
U HV	10	DIN EN ISO	6507-1.201	8-07			
_		DIN EN ISO		19 23			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test temp	peratur, if ou	tside (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV		Hereitere	237 HV 10
Indentation	d,	d₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	2010/02/02
1	287,1	289,1	0,2881	223			
2	287,1	289,1	0,2860	223			
3	285,2	287,1	0,2861	227	227		BM 1
4	282,7	286,0	0,2844	229			Binit
5	282,9	287,7	0,2853	228			
1	290,4	290,6	0,2905	220			
2	288,5	291,4	0,2900	221			
3	290,6	293,3	0,2919	218 219	220		HAZ 1
4	291,4 284,4	290,4 291,2	0,2909 0,2878	219			
1	285,8	279,8	0,2878	232	-		
2	283,1	285,6	0,2844	229		-	
3	285,2	284,8	0,2850	228	228	-	WM
4	288,9	286,0	0,2875	224			
5	284,8	287,7	0,2862	226			
1	286,6	286,4	0,2865	226			
2	284,4	289,5	0,2870	225	000		HAZ 2
3	280,2	284,8	0,2825	232	228		
4	285,2 283,8	282,3 288,3	0,2837 0,2860	230 227			
1	288,1	200,3	0,2898	221			
2	287,7	288,9	0,2883	223			
3	283,3	288,7	0,2860	227	227		BM 2
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)

\mathbb{N}	STUTTGA	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)		64000	Contraction in	TERM
Sample desc	ription	17.1; Roo	t				and the second
Administrat	or	Silcher					
		None Includes the sector to street to					
Test instrum		Zwick Z 323	23-11-122-1			and the second	
Serial numbe	er	H2932-002-	50430				
Test conditio	ns					X and p	
J HV	10	DIN EN ISO	6507-1:201	8-07			
- HBW		CENTRAL SERVICES	6506-1:201	Manager			
HRC			6508-1:201				
	Test temp	peratur, if out	tside (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference	237 HV 10
plate	μm	μm	mm	HV		Herefeller	237 HV 10
Indentation	d,	d₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	2010/02/2015
1	285,2	202.1	0.2901	222			
2	285,2	293,1 291,0	0,2891 0,2890	222			
3	287,1	292,7	0,2899	221	220		BM 1
4	289,3	294,3	0,2918	218			
5	290,6	294,1	0,2923	217			
1	286,0	288,3	0,2872	225			
2	282,3	282,3	0,2823	233	10000000		
3	280,6	282,1	0,2814	234	231		HAZ 1
4	280,2	278,3	0,2793	238			
5 1	286,0 284,2	285,8 285,8	0,2859 0,2850	227 228			e,
2	278,8	285,8	0,2850	228			
3	281,2	283,5	0,2790	237	229		WM
4	287,7	287,7	0,2024	233			
5	286,4	290,0	0,2882	223	1		
1	296,8	293,3	0,2950	213			
2	287,7	284,4	0,2860	227			HAZ 2
3	285,0	286,4	0,2857	227	230		
4	279,8	275,0	0,2774	241			
5	274,8	278,1	0,2765	243			
1	286,4 285,0	285,8 289,3	0,2861 0,2872	227 225		-	2
3	285,0	289,3	0,2872	225	229		BM 2
4	283,7	287,9	0,2858	227	220		
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)

\mathbb{N}	STUTTGA		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	Referat etallographie und tronenmikroskopie		
Order numb	er	9039784000)						
Sample desc	ription	17.2; Outer	layer				Carl In a sure of		
Administrat	or	Silcher			a state of				
Test instrum			(nou)			Station Days	1 5 1 1		
		Zwick Z 323	23-11-12						
Serial number	er	H2932-002-	50430						
Test conditio	ns								
U HV	10	DIN EN ISO	6507-1:201	8-07	-				
HBW		DIN EN ISO	6506-1:201	5-02					
		DIN EN ISO	6508 1.201	6.12					
	-								
	A CHOOM STREET	peratur, if out	apport in work of the			1.000	1		
Control plate	280,6	280,8	0,281 mm	235 HV		Reference:	237 HV 10		
ST STOLDER DO NET HOUT T	µm d₁	µm d ₂	d _m	Language Course of Language	Mean value	Distance in	-		
Indentation no.	μm	μm	mm	Hardness HV	HV HV	mm	Remark		
1.77		Part							
1	284,4	293,9	0,2891	222					
2	285,2	290,2	0,2877	224			5144		
3	286,0	286,9	0,2864	226 224	223		BM 1		
4	286,2 289,1	289,8 291,8	0,2880	224					
1	209,1	291,8	0,2905	220					
2	293,3	288,5	0,2909	219					
3	294,1	291,0	0,2926	217	214		HAZ 1		
4	296,4	293,3	0,2949	213	12-22-20				
5	302,8	299,7	0,3013	204					
1	282,9	286,6	0,2848	229					
2	285,4	282,1	0,2837	230			WM		
3	287,1	284,6	0,2858	227	229				
4	285,6 285,4	281,7	0,2836 0,2855	231			4		
5	285,4	285,6 290,4	0,2855	228 217	-	-			
2	294,0	290,4	0,2925	217			1		
3	281,7	282,3	0,2820	233	220		HAZ 2		
4	288,5	292,4	0,2905	220			1		
5	301,0	301,4	0,3012	204	· · · · · · · · · · · · · · · · · · ·				
1	289,8	289,8	0,2898	221					
2	285,6	288,1	0,2869	225					
3	286,7	289,5	0,2881	223	224		BM 2		
4	283,7	287,1	0,2854	228					
5	285,8	290,4	0,2881	223					
Date:	06.11.22	4							
Tester	School								
Tester:	Scheck								

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

\mathbb{N}	STUTTG/		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000	í.				
Sample desc	ription	17.2; Root		Cherry and			ANT CAR
Administrat	or	Silcher					
Test instrum		Zwick Z 323	(neu)				And the second
Serial number	er	H2932-002-	50430			a start and the	
Test conditio	ns					A CARLES	
U HV	10	DIN EN ISO	6507-1:201	8-07		2.	
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1-201	6-12			
	Test	peratur, if ou					
	A CONTRACTOR	and the state of the state of the state	NIDOSCIUS MORESCIAI				
Control plate	280,6	280,8	0,281	235 HV		Reference:	237 HV 10
	μm	μm	mm			Distance in	
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
110.	Paul	pin					
1	287,1	292,5	0,2898	221			
2	287,7	290,4	0,2890	222	2020		
3	288,7	293,3	0,2910	219	220		BM 1
4	289,8	293,9	0,2918	218			
5	286,9 308,0	292,7 309,3	0,2898	221 195			-
2	308,0	309,3	0,3086	200			1
3	295,4	299,1	0,2972	210	204	-	HAZ 1
4	300,8	299,9	0,3003	206	204		
5	295,4	296,4	0,2959	212			
1	314,7	293,5	0,3041	201		7	
2	292,9	295,6	0,2942	214			
3	292,5	290,6	0,2915	218	212		WM
4	293,9	296,0	0,2949	213			4
5	296,2	295,4	0,2958	212			
1	307,4	305,5	0,3065	197		1	4
2	298,1 296,6	302,8 298,1	0,3004 0,2974	205 210	210		HAZ 2
4	290,0	298,1	0,2974	210	210		1
5	292,7	290,4	0,2912	213		-	1
1	285,4	288,9	0,2872	225			
2	282,7	286,7	0,2847	229			1
3	285,6	290,8	0,2882	223	228		BM 2
4	282,3	285,4	0,2838	230]
5	281,0	285,8	0,2834	231			
	06.11.22 Scheck	1					1

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

no. µm µm mm HV HV HV mm etcode 1 232,5 231,6 0,2321 344 350 351 14 14 228,5 229,6 230,2 0,2299 351 351 14 223,7 233,3 0,2395 355 14 1233,7 233,3 0,2395 340 14 235,8 238,9 0,2374 329 334 14 14 235,8 238,9 0,2374 329 334 14AZ 1 4 235,8 238,1 0,2364 332 332 334 14AZ 1 5 233,9 233,5 0,2337 339 345 144 235,0 228,7 0,2317 339 345 142 230,0 228,7 0,2319 345 142 345 142 323,0 228,7 0,2317 346 142 231,0 0,2326 343 142 231,0 0,2326 343 142 233,3	\mathbb{N}	STUTTG	ART	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat ographie und enmikroskopie
Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions P HV 10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6508-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/5)*C Control 200,6 200,8 0,281 235 Indentation d, d, d, d, mm HV Mean value Distance in mm Indentation d, 1 4 24,230,2 0,2301 350 3 220,6 230,2 0,2301 350 351 BM 1 4 228,5 228,7 0,2286 355 351 BM 1 4 228,5 228,6 0,2301 350 324 442 2 230,0 230,2 0,2386 334 HAZ 1 4 228,5 0,2381 334 40 42 2 230,0 232,9 0,2326 344 345 WM 1 233,0 233,5 0,2335 <	Order numb	er	9039784000)				
Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions Image: Condition of the conditis of the condition of the conditis of the condition of	Sample descr	ription	40.1; Outer	layer				
Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions H2932-002-50430 HV 10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6508-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) °C Reference: 237 HV 10 Indentation d1 d2 230,0 230,2 0.2281 344 2 230,0 230,2 0.2301 350 BM 1 1 232,5 231,6 0.2321 344 Prive BM 1 3 229,6 230,2 0.2301 350 351 BM 1 4 228,5 228,7 0.2280 354 BM 1 4 228,5 228,7 0.2386 332 344 HAZ 1 5 223,8 238,8 0.2387 334 HAZ 1 4 228,5 238,9 0.2387 349 345 5 233,9 233,5 0	Administrato	or	Silcher					
Serial number H2932-002-50430 Test conditions Intermediate H2932-002-50430 Her DIN EN ISO 6507-1:2018-07 Intermediate Intermediate <thintermediate< th=""> <thintermediate< th=""></thintermediate<></thintermediate<>	Test instrum	ent		(neu)	and the second			
Interest conditions Image: HV 10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-02 Test temperatur, if outside (23+/5)*C Reference: 237 HV 10 Indentation d1 d2 dm Hardness Mean value Distance in mm Remark 1 232,5 231,6 0,2321 344								
Image: Hv 10 DIN EN ISO 6507-1:2018-07 Image: Hv DIN EN ISO 6508-1:2015-02 DIN EN ISO 6508-1:2016-12 Distence In It <td>1/ 0</td> <td></td> <td>H2932-002-</td> <td>50430</td> <td></td> <td></td> <td>N. States St.</td> <td></td>	1/ 0		H2932-002-	50430			N. States St.	
HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) *C Control 280,6 280,8 0,281 233 Indentation d1 d2 d4 Hardness Mean value Distance in mm Reference: 237 HV 10 Indentation d1 d2 230,2 0,2301 350 351 BM 1 2 230,0 230,2 0,2301 350 351 BM 1 4 228,5 228,5 0,2289 351 351 BM 1 4 228,6 228,5 0,2285 355	Test conditio	ns					And Andrews	
HRC DIN EN ISO 6508-11:2016-12 Test temperatur, if outside (23+4-5) *C Controi 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation d ₁ d ₂ d ₃ d ₄ d ₄ d ₄ Hardness Mean value Distance in mm Remark 1 232,5 231,6 0,2321 344	⊡ HV 1	10	DIN EN ISO	6507-1:201	8-07		142.37	
Test temperatur, if outside (23+/-5) *C Control plate Z80,6 280,8 0,281 Z35 Reference: Z37 HV 10 Indentation no. d ₁ d ₂ d _m Hardness Mean value Distance in mm Reference: Z37 HV 10 1 232,5 231,6 0,2321 344 Hardness Mean value Distance in mm Remark 2 230,0 230,2 0,2301 350 351 BM 1 4 228,5 228,5 0,2289 354 BM 1 1 233,7 233,3 0,2335 340 HAZ 1 2 237,4 235,4 0,2364 332 334 HAZ 1 3 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,1 0,2369 330 HAZ 1 4235,0 228,7 0,2316 345 WM 3 230,2 232,9 0,2329 342 4233,1 230,0 228,7	🗆 HBW		DIN EN ISO	6506-1:201	5-02		ALC: NO	
Test temperatur, if outside (23+/-5) *C Control plate Z80,6 280,8 0,281 Z35 Reference: Z37 HV 10 Indentation no. d ₁ d ₂ d _m Hardness Mean value Distance in mm Reference: Z37 HV 10 1 232,5 231,6 0,2321 344 Hardness Mean value Distance in mm Remark 2 230,0 230,2 0,2301 350 351 BM 1 4 228,5 228,5 0,2289 354 BM 1 1 233,7 233,3 0,2335 340 HAZ 1 2 237,4 235,4 0,2364 332 334 HAZ 1 3 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,1 0,2369 330 HAZ 1 4235,0 228,7 0,2316 345 WM 3 230,2 232,9 0,2329 342 4233,1 230,0 228,7					2010			
Control plate 280,6 µm 280,8 µm 0,281 µm 235 HV Reference: 237 HV 10 Indentation no. d1 µm d2 µm dm µm Hardness HV Mean value HV Distance in mm Remark 1 232,5 231,6 0,2321 344 Image: State in the image: St		Test tops			No. of Street,			
plate µm µm mm HV Indentation d1 d2 dm Hardness Mean value Distance in Remark 1 232,5 231,6 0,2321 344 Remark 1 232,5 230,2 0,2301 350 </td <td></td> <td>A CHORENE LIPPONTA</td> <td>The second second second second second</td> <td>ILCOSE INCREMENTS</td> <td></td> <td></td> <td>1 Witter</td> <td>Town and the second</td>		A CHORENE LIPPONTA	The second second second second second	ILCOSE INCREMENTS			1 Witter	Town and the second
Indentation no. d, µm d, µm d, µm Hardness mm Mean value HV Distance in mm Remark 1 232,5 231,6 0,2321 344 1 <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>Reference:</td> <td>237 HV 10</td>							Reference:	237 HV 10
no. µm µm mm HV HV mm mm HV mm mm HV mm mm HX	-					Mean value	Distance in	
1 232,5 231,6 0,2321 344 2 230,0 230,2 0,2301 350 3 229,6 230,2 0,2299 351 351 4 228,5 228,5 0,2285 355 55 5 229,2 228,7 0,2289 354 56 1 233,7 233,3 0,2374 329 334 HAZ 1 2 237,4 235,4 0,2369 330 334 HAZ 1 3 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,1 0,2369 330 350 342 344 2 323,0 232,9 0,2315 346 345 WM 4 235,0 228,7 0,2319 345 44 230,0 2232,9 0,2326 343 3 230,2 232,1 0,2326 343 343 44 4233,1 233,3 0,2325 343 1 230,0 223,4 0,2327 352	THE STORY STORY	655 CT	2010/06/07	5-32,0049		The second s		Remark
2 230,0 230,2 0,2301 350 351 BM 1 3 229,6 230,2 0,2299 351 351 BM 1 4 228,5 228,5 0,2285 355 351 BM 1 1 233,7 233,3 0,2335 340 340 323,8 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,9 0,2374 329 334 HAZ 1 5 233,9 233,5 0,2301 350 350 340 341 2 232,9 232,9 0,2329 342 345 MWM 4235,0 228,7 0,2315 346 345 WM 4 235,0 228,7 0,2326 343 343 HAZ 2 4233,1 233,3 0,2326 343 343 HAZ 2 HAZ 2 4233,1 233,3 0,2326 343 343 HAZ 2 HAZ 2 4233,1 233,3 0,2326 343 343 HAZ 2 HAZ 2 4233,1 233,3 0,2315 346 <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>59016657</td> <td></td>							59016657	
3 229,6 230,2 0,2299 351 351 351 BM 1 4 228,5 228,5 0,2285 355 355 351 BM 1 1 233,7 233,3 0,2335 340 334 HAZ 1 2 237,4 235,4 0,2369 330 334 HAZ 1 4 235,8 238,9 0,2317 339 334 HAZ 1 4 235,8 238,1 0,2301 350 350 342 345 MUM 2 232,9 232,9 0,2315 346 345 MUM								
4 228,5 229,5 0,2285 355 5 229,2 228,7 0,2289 354 1 233,7 233,3 0,2335 340 2 237,4 235,4 0,2364 332 3 235,8 238,9 0,2374 329 334 4 255,8 238,9 0,2374 329 334 1 234,1 226,0 0,2301 350 2 232,9 232,9 0,2315 346 345 3 230,0 228,7 0,2315 346 345 WM 4 235,0 228,7 0,2319 345 HAZ 1 4 230,0 229,4 0,2297 352 2 232,9 232,1 0,2325 343 343 HAZ 2 3 233,1 233,3 0,2326 343 343 1 230,8 228,9 0,2299 351 346 2						054		
5 229,2 228,7 0,2289 354 1 233,7 233,3 0,2335 340 2 237,4 235,4 0,2364 332 3 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,1 0,2364 332 334 HAZ 1 4 235,8 238,1 0,2307 339 334 HAZ 1 2 232,9 232,9 0,2317 339 345 WM 3 230,2 232,9 0,2315 346 345 WM 4 235,0 228,7 0,2316 343 345 WM 5 231,9 233,3 0,2326 343 345 HAZ 2 2 232,9 232,1 0,2325 343 343 HAZ 2 4 233,1 233,3 0,2326 343 343 HAZ 2 2 230,8 228,9 0,2297 352						- 351		BM 1
1 233,7 233,3 0,2335 340 2 237,4 235,4 0,2364 332 3 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,1 0,2369 330								1
2 237,4 235,4 0,2364 332 332 334 HAZ 1 3 235,8 238,9 0,2374 329 334 HAZ 1 4 235,8 238,1 0,2369 330 334 HAZ 1 1 234,1 226,0 0,2301 350 350 342 345 MM 3 230,2 232,9 0,2329 342 345 MM WM 4 235,0 228,7 0,2315 346 345 MM MM 5 231,9 233,3 0,2326 343 345 MM HAZ 2 2 232,9 232,1 0,2325 343 343 HAZ 2 HAZ 2 2 232,9 235,4 0,2315 343 343 HAZ 2 HAZ 2 4 233,1 233,3 0,2326 343 343 HAZ 2 HAZ 2 2 232,9 235,4 0,2341 338 343 HAZ 2 HAZ 2 3 230,6 231,4 0,2310 <td< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-</td></td<>								-
4 235,8 238,1 0,2369 330 5 233,9 233,5 0,2337 339 1 234,1 226,0 0,2301 350 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 2 232,9 232,1 0,2326 343 3 234,1 231,0 0,2326 343 3 234,1 233,3 0,2326 343 3 234,1 233,3 0,2326 343 3 234,1 233,3 0,2321 343 4 233,1 233,3 0,23241 338 1 230,8 228,9 0,2299 351 2 230,8 232,3 0,2315 346 3 230,6 231,4 0,2313 347		237,4	235,4				[1
5 233,9 233,5 0,2337 339						334		HAZ 1
1 234,1 226,0 0,2301 350 2 232,9 232,9 0,2329 342 3 230,2 232,9 0,2315 346 345 4 235,0 228,7 0,2319 345 345 5 231,9 233,3 0,2326 343 45 1 230,0 229,4 0,2297 352 433 2 232,9 232,1 0,2325 343 343 3 234,1 231,0 0,2326 343 343 4 233,1 233,3 0,2326 343 343 5 232,9 235,4 0,2312 341 343 1 230,8 228,9 0,2299 351 346 2 230,8 232,3 0,2315 346 346 3 230,6 231,4 0,2310 347 346 BM 2 4 231,6 231,0 0,2313 347 346 BM 2 5 233,3 233,5 0,2334 3								
2 232.9 232.9 0,2329 342 3 230.2 232.9 0,2315 346 345 345 4 235.0 228.7 0,2319 345 345								
3 230,2 232,9 0,2315 346 345 WM 4 235,0 228,7 0,2319 345							-	
4 235,0 228,7 0,2319 345 5 231,9 233,3 0,2326 343 1 230,0 229,4 0,2297 352 2 232,9 232,1 0,2325 343 3 234,1 231,0 0,2326 343 3 234,1 231,0 0,2326 343 4 233,1 233,3 0,2322 341 5 232,9 235,4 0,2341 338 1 230,8 228,9 0,2299 351 2 230,8 232,3 0,2315 346 3 230,6 231,4 0,2310 347 3 231,6 231,0 0,2313 347 5 233,3 233,5 0,2334 340						345		WM
1 230,0 229,4 0,2297 352	4	235,0	228,7	0,2319	345	1000-10040-000		1
2 232,9 232,1 0,2325 343 343 HAZ 2 3 234,1 231,0 0,2326 343 343 HAZ 2 4 233,1 233,3 0,2332 341 1 <td< td=""><td>5</td><td>231,9</td><td></td><td></td><td></td><td></td><td></td><td></td></td<>	5	231,9						
3 234,1 231,0 0,2326 343 343 HAZ 2 4 233,1 233,3 0,2332 341 1 <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>-</td>								-
4 233,1 233,3 0,2332 341 5 232,9 235,4 0,2341 338 1 230,8 228,9 0,2299 351 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						342		ΗΔ7 2
5 232,9 235,4 0,2341 338 1 230,8 228,9 0,2299 351 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						343		
1 230,8 228,9 0,2299 351 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								1
3 230,6 231,4 0,2310 347 346 BM 2 4 231,6 231,0 0,2313 347 100 100 5 233,3 233,5 0,2334 340 100 100 Date: 06.11.22								
4 231,6 231,0 0,2313 347 5 233,3 233,5 0,2334 340 Date: 06.11.22					and the second sec	2007-C-		
5 233,3 233,5 0,2334 340 Date: 06.11.22						346		BM 2
Date: 06.11.22					and the second se			4
	5	200,0	200,0	0,2004	340			1
	Date:	06 11 22					ý	
Taster: Scherk	Dates	00.11.22						
Tester, Suller	Tester:	Scheck						

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

\mathbb{N}	STUTTG		MF	AS-PPB 523	Test report F MPAS-PPB 52310-08/1 Meta Hardness test Elektro				
Order numb	er	9039784000)						
Sample desc	ription	40.1; Root	t.						
Administrate	or	Silcher							
Test instrum		Zwick Z 323	(nou)						
						An all all and a set of the			
Serial numbe		H2932-002-	50430						
Test conditio	ns					and the second second			
U HV ·	10	DIN EN ISO	6507-1:201	8-07					
HBW		DIN EN ISO	6506-1:201	5-02					
		DIN EN ISO		11000					
	Tank tan	peratur, if out							
	A CHOOM SHOW	states de la colmente de des	and one in the second second	STATISTICS.		11100 m	Transfer of the second second		
Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10		
Indentation	d,	d ₂	dm		Mean value	value Distance in	-		
no.	μm	μm	mm	Hardness HV	HV	mm	Remark		
1	232,9	232,3	0,2326	343					
2	231,7	230,2	0,2309	348	050				
3	229,8 229,8	230,8 228,9	0,2303 0,2294	350 352	350		BM 1		
4	229,8	228,9	0,2294	352		-			
1	229,6	228,9	0,2293	353	-				
2	227,7	227,9	0,2278	357					
3	227,7	224,2	0,2259	363	365		HAZ 1		
4	218,8	220,6	0,2197	384					
5	224,6	225,2	0,2249	367	econored		***************		
1	228,9 234,5	232,3 230,8	0,2306	349 343	(
3	234,5	230,8	0,2327	343	366		WM		
4	216,9	217,1	0,2170	394					
5	220,0	218,4	0,2192	386					
1	241,6	243,1	0,2423	316					
2	229,2	230,2	0,2297	352	245	-			
3	229,6 230,2	227,7 230,0	0,2286 0,2301	355 350	345	-	HAZ 2		
5	229,8	230,0	0,2301	351					
1	228,7	228,3	0,2285	355					
2	228,5	230,6	0,2296	352					
3	231,0	230,4	0,2307	348	350		BM 2		
4	230,0	230,8	0,2304	349 347					
5	231,6	230,8	0,2312	347					
Date:	06.11.22	•				b	J.		
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:

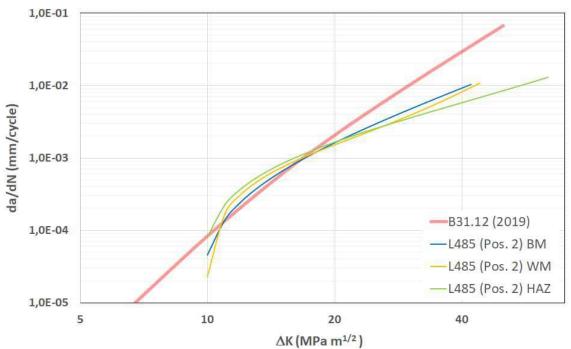
Table 3.67: Characteristics of L485

Production year	2009	
Production standard	DIN EN ISO 37	183 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

Ob anaioral a sman a sitism	С	Si	Mn	Ρ	S	Cu	Cr	Мо
Chemical composition	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:



L485 (Pos. 2)

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.

\mathbb{N}	stutte		Test repo MPAS-PPB 5231 Hardness t		10-08/1	Metallo	eferat graphie und enmikroskopie
Order numb	er	9039784000	0	12			
Sample descr	iption	2.1 Outer I	ayer				-
Administrato	or.	Silcher	100 - 10 - 10 - 10 - 10 - 10 - 10 - 10				
		0.000204046	- ACCHONDANC	1			
Test instrum	ent	Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ns			W.			
⊡ HV 1	10	DIN EN ISC	6507-1-201	8-07			
нвw		INCOMPANY AND AN ANY AND ANY	6506-1:201		-		
HRC		DIN EN ISC	6508-1:201	6.12			-
	Test						
	A CHORNEL LAND	peratur, if ou	SUDORCH CRACKORS			1.000	Transformer and the
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
	μm	μm	mm	HV			
Indentation no.	d₁ µm	dz µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
110.	pan	pm		nv			
1	285,0	283,1	0,2841	230			
2	282,1	285,8	0,2839	230			
3	281,2	287,1	0,2841	230	228		BM 1
4	282,5	289,5	0,2860	227		4	
5	280,0	295,4	0,2877	224			
1	312,6	306,4	0,3095	194			HAZ 1
2	299,9 297,2	299,9 297,6	0,2999 0,2974	206	207	1	
4	295,6	297,0	0,2969	210	207		
5	293,7	297,2	0,2955	212			
1	293,1	298,1	0,2956	212			
2	292,9	297,9	0,2954	213	1 1	1	
3	292,0	293,9	0,2930	216	214		WM
4	292,7	294,1	0,2934	215	1 1		1
5	295,4	292,9	0,2941	214		l	
1	303,2	304,9	0,3041	201			
2	302,6	297,8	0,3002	206	24465		HAZ 2
3	297,9	294,9	0,2964	211	208		
4	302,6	292,7	0,2977	209			
5	298,7	294,7	0,2967	211			
1	275,2 273,4	287,3 283,9	0,2812 0,2787	234 239			
3	273,4	285,9	0,2787	239	238		BM 2
4	273,4	283,8	0,2801	230	230		
5	272,3	284,8	0,2786	239			
Date: (06.11.22						

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

\mathbb{N}	STUTTG	\sim	MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	ferat graphie und nmikroskopie
Order numb	er	9039784000)	16			
Sample descr	ription	2.1 Center		-	1000		Constant of the local division of the local
Administrato				10.53			
		Silcher		1.00			
Test instrum	ent	Zwick Z 323	(neu)	1000	-	A CARLES	
Serial numbe	er	H2932-002-	50430		-		
Test conditio	ns			100			
	10	DINENUEO	6507-1:201	0.07			
			270.31 N. 70.70.5	1		~	
		A CONTRACTOR OF A CONTRACTOR	6506-1:201				
HRC		DIN EN ISC	6508-1:201	6-12			
	Test tem	peratur, if ou	itside (23+/	-5) °C			
Control	280,6	280,8	0,281	235		Rafaranca	237 HV 10
plate	μm	μm	mm	HV		neierence:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Action
1	287.7	286,4	0,2871	225			
2	287,5	289.5	0,2871	223			
3	283.9	290,0	0,2870	225	226		BM 1
4	279,8	289,6	0,2847	229	1.505555		
5	281,3	288,5	0,2849	228			
1	294,3	293,1	0,2937	215			
2	297,9	297,0	0,2974	210			HAZ 1
3	295,1	295,8	0,2955	212	208		
4	302,4	302,2 302,2	0,3023	203 201			
5	305,3 299,9	302,2	0,3038	201			
2	299,9	293,1	0,3007	218			
3	294,3	292,7	0,2915	215	213		WM
4	295,8	292,7	0,2942	214	1.111		
5	291,6	295,6	0,2936	215			
1	295,8	294,5	0,2952	213			
2	298,7	295,6	0,2971	210			HAZ 2
3	299,3	294,1	0,2967	211	210		
4	293,7	294,1	0,2939	215			
5	302,4	303,5	0,3029	202			
1	282,9 288,1	293,9 297,0	0,2884 0,2926	223			
3	285,8	297,0	0,2926	217	220		BM 2
4	285.0	294,5	0,2915	221	220		
5	283,1	294,7	0,2889	222			
Date: (06.11.22						

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

\mathbb{N}	STUTTG		M	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	eferat graphie und enmikroskopie
Order numb	er	9039784000)	1.6	-		
Sample descr	iption	2.1 Root			and the second sec		
Administrato	1.8 C - 3.9 C - 3.0 C	21222-024)					
		Silcher					
Test instrum	ent	Zwick Z 323	(neu)	100			
Serial numbe	r	H2932-002-	50430	1.000			
Test conditio	ns						
	10	DIN 51 100	0007 4 004	0.07	A		
	10	DIN EN ISO			the second second		J
HBW		DIN EN ISO	6506-1:201	5-02	6 ····		
HRC		DIN EN ISO	6508-1:201	6-12	and the second se		
	Test tem	peratur, if ou	tside (23+/	-5) *C			
Control	280,6	280,8	0,281	235		Pafaranta	00710140
plate	μm	μm	mm	HV		nererence:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	nemark
	271,9	270,3	0,2711	252			
2	267,8	270,3	0,2728	232	1 1		1
3	268,6	280,0	0,2743	246	247		BM 1
4	269,8	281,7	0,2757	244	3633		
5	269,4	283,7	0,2766	242			
1	283,7	289,5	0,2866	226			
2	289,8	293,1	0,2914	218		1	
3	291,0	293,9	0,2925	217	219		HAZ 1
4	290,6	291,8	0,2912	219			
5	290,6	293,7	0,2922	217			
1	280,0 287,5	281,5	0,2807	235			
3	287,5	284,6	0,2860	227	228	-	WМ
4	286,2	280,2	0,2862	226	220		
5	288,1	287,3	0,2831	224	1 1	1	1
1	286,7	291.0	0,2888	222			
2	293,5	291,8	0,2927	217	1 1	1	1
3	291,5	291,0	0,2913	219	217		HAZ 2
4	295,4	294,5	0,2950	213	68/025		1
5	289,8	298,5	0,2941	214			
1	265,1	282,1	0,2736	248			
2	264,0	273,4	0,2687	257			
3	262,6	274,4	0,2685	257	255		BM 2
4	262,4	275,4	0,2689	256			
5	261,9	274,4	0,2682	258			
		1					
Date: 0	6.11.22						
Duter (W. 11.66						
Tester: §	Scheck						

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

\mathbb{N}	атита,		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	graphie und enmikroskopie
Order numb	er	9039784000)		000		
Sample descr	iption	2.2 Outer l	ayer	30			
Administrato	or	Silcher	and a second	1		CO.	
		Carlor Carlo	58017/51	1.1.1			
Test instrum		Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430			Contraction of	
Test conditio	ns			1			
⊡ HV 1	10	DIN EN ISC	6507-1-201	8-07			6
□ HBW		10.000.000000000	L'EXPERIMENTAL CONTRACTOR	and the second second		A Company	1
		A STREET, STRE	6506-1:201				1
HRC		DIN EN ISC	6508-1:201	6-12			
	Test tem	peratur, if ou	tside (23+/	-5) *C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV		increased.	257 114 10
Indentation	d,	d₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	20038020002
1	268,4	277,1	0,2727	249		-	
2	265,7	280,0	0,2728	249		0_11111111111	
3	268,4	280,8	0,2746	246	246	1	BM 1
4	269,0	282,3	0,2756	244	10000000		
5	270,0	285,4	0,2777	240			
1	294,0	292,0	0,2930	216			
2	294,1	297,8	0,2960	212			
3	288,9 298,5	298,5 294,7	0,2937 0,2966	215	214		HAZ 1
5	298,5	294,7	0,2966	219			
1	291,0	291,4	0,2912	219			
2	293,7	294,5	0,2941	214		1	
3	289,5	290,2	0,2899	221	218		WM
4	291,4	291,4	0,2914	218		l.	
5	292,5	291,2	0,2918	218			
1	317,6	314,7	0,3161	186			
2	289,6	288,1	0,2888	222	212		HAZ 2
3	290,0 286,2	297,0 290,0	0,2935	215 223	213		
5	295,2	290,0	0,2861	218			
1	279,4	291,6	0,2855	227			
2	278,8	289,3	0,2840	230			1
3	276,1	288,3	0,2822	233	230		BM 2
4	277,7	288,3	0,2830	232			
5	282,3	290,6	0,2864	226			
1.0040 C.	1000 C					Ji ji	
Date: (06.11.22						
Tester:	Scheck						

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

\mathbb{N}	stutte		М	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	graphie und enmikroskopie
Order numb	er	9039784000	0	6	000 .	~	
Sample desc	ription	2.2 Center		100		1. 19 C	1
and the second second second second	A CONTRACTOR OF CONTRACTOR			200			
Administrate		Silcher		2.00			
Test instrum	ent	Zwick Z 323	(neu)	1.00			
Serial numbe	er	H2932-002-	50430	1		- And	
Test conditio	ns			-24			
	10	DIN EN ISC	6507-1:201	8-07			Le la se
		MERARSOLFACORUR	6506-1:201	ALL STREET, ST		Jac L	1
		ESERVISION DE DES	6508-1:201		Same -		the second second
		122210-00220-2		3. J. State			
	A STREET, STRE	peratur, if ou					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	d2	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	233,261253055.
	000.0	000.0	0.0000	004			
1	286,2 281,5	293,3 292,9	0,2898	221 225	4 F		
3	279,6	292,9	0,2872	225	226		BM 1
4	279,4	290,4	0.2849	228	22.0		DIVI I
5	280,6	291,2	0,2859	227			
1	296,6	291,8	0,2942	214			
2	291,4	292,0	0,2917	218			
3	292,2	292,9	0,2926	217	211		HAZ 1
4	299,3	297,2	0,2983	208			
5	304,5 291,4	307,6	0,3060 0,2910	198		-	
2	291,4	290,6 288,3	0,2910	219			
3	295.8	297.2	0,2965	211	215		WM
4	294,1	285,4	0,2898	221	2.10		
5	302,6	302,0	0,3023	203			
1	292,0	292,9	0,2925	217			
2	294,3	292,9	0,2936	215	20222-024		
3	290,8	296,8	0,2938	215	214		HAZ 2
4	294,3	294,1	0,2942	214			
5	298,1	299,1	0,2986	208			
2	280,4 279,2	288,5 282,9	0,2845	229		-	
3	283,5	202,5	0,2868	225	230	r	BM 2
4	279.0	288,7	0,2838	230	200		
5	280,2	288,7	0,2845	229	I		
			220110 00000				
	06.11.22 Scheck						

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

\mathbb{N}	STUTTG		Test rep MPAS-PPB 523 Hardness		10-08/1	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)	100	000 -	1		
Sample desc	ription	2.2 Root		17.20			And the second s	
Administrato	C. Second and the second	14-2010		200				
		Silcher		100				
Test instrum	ent	Zwick Z 323	(neu)					
Serial numbe	er	H2932-002-	50430			A State		
Test conditio	ns			- 100				
	10	DIN EN ISC	6507-1:201	8.07	-	1		
□ HBW			6506-1:201	and a large		and a	1	
		Martin Contraction	and the second second					
HRC			6508-1:201					
	Test temp	peratur, if ou	tside (23+/-	-5) *C				
Control	280,6	280,8	0,281	235		Reference:	227 HV 40	
plate	μm	μm	mm	HV		nererence.	237 11 10	
Indentation	d,	d2	d _m	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	ACTION K	
	000.0	0711	0.0005	0.57				
1	262,6 258,0	274,4	0,2685	257 260				
2	261,3	276,5	0,2672	258	256		BM 1	
4	262,2	276,3	0,2692	256	200		DIVI I	
5	267,3	280,8	0,2741	247	1 1			
1	287,7	289,1	0,2884	223				
2	290,4	296,6	0,2935	215			HAZ 1	
3	293,7	292,5	0,2931	216	216			
4	296,2	294,8	0,2955	212	1.000			
5	294,7	294,3	0,2945	214	1	1		
1	289,8	291,2	0,2905	220			-1	
2	288,7	287,7	0,2882	223				
3	292,7	287,9	0,2903	220	222		WM	
4	286,2	287,1	0,2866	226				
5	291,2	290,0	0,2906	220				
1	289,3	286,8	0,2881	223				
2	291,0 284,6	288,3 290,4	0,2896	221 224	222		HAZ 2	
4	284,6	290,4	0,2875	224	222			
5	294,7	205,0	0,2856	214				
1	269,6	281,7	0,2340	244			- -	
2	267,6	280,6	0,2741	247		-1		
3	264,6	278,3	0,2715	252	248		BM 2	
4	265,1	276,3	0,2707	253	No contra de la co		2.07 2	
5	269,4	280,2	0,2748	246				
					1		1	
Date:	06.11.22							
Juice 1	0.11.62							

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

Ob anni a al a a man a aiti a n	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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 _{Jlc} [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.

- 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 $^\circ \rm C$

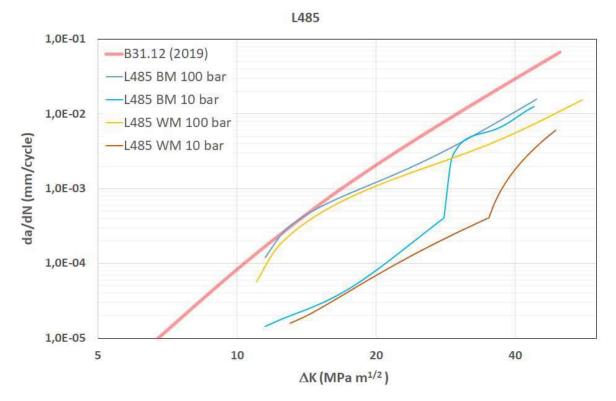


Figure 3.99: Crack growth L485

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 31	83, 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)

Ob emised economic sitism	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	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.

- base material
- weld material

 $^{^{21}}$ Notched-bar impact test as per Charpy (DIN EN ISO 148) with V-notch at 20 $^\circ \rm C$

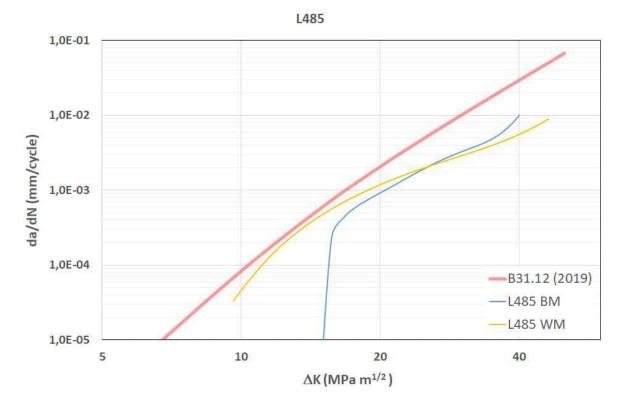


Figure 3.100: Crack growth L485 (batch 2)

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.

			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie				
Order numb	er	9039784000	1	/						
Sample description		47.1 Outer	layer	and the second second						
Administrator Test instrument Serial number		Silcher		1						
		Zwick Z 323	(nou)	4						
		H2932-002-50430								
Test conditio	ns									
 ✓ HV 10 □ HBW 		DIN EN ISO 6507-1:2018-07								
		DIN EN ISO 6506-1:2015-02								
HRC		DIN EN ISO 6508-1:2016-12								
7	Test tem	peratur, if ou								
Control	280,6	280.8	0,281	235		2352	Terrer Marcola			
plate	μm	μm	mm	HV		Reference:	237 HV 10			
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in				
no.	μm	μm	mm	HV	HV	mm	Remark			
	4144684									
1	313,8	327,1	0,3205	181	186					
2	313,6 309,3	327,3 320,3	0,3205	181 187			BM 1			
4	297,6	314,0	0,3148	198						
5	308,0	325,5	0,3167	185						
1	308,6	311.5	0,3101	193						
2	289,3	296,6	0,2930	216			HAZ 1			
3	294,5	295,4	0,2949	213	206					
4	298,1	298,9	0,2985	208						
5	303,5	302,2	0,3028	202						
1	286,9	291,0	0,2889	222						
2	291,2	289,8	0,2905	220	218	-	WМ			
3	294,3 294,5	290,8 292,9	0,2926	217 215						
5	294,5	289,3	0,2937	213						
1	295,3	294,2	0,2948	213						
2	299,5	296,8	0,2982	209	211		HAZ 2			
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	314,3 311,6	326,7 326,3	0,3205 0,3189	181 182						
4	312,6	320,3	0,3183	183						
5	315,1	329,0	0,3220	179			-			
			_							
Date:	06.11.22									
Tartar	Cohoole									
Tester:	Scheck									

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

			MF	Test rep PAS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie					
Order numb	er	9039784000)								
Sample description		47.1 Cente		10 Martin							
Administrator Test instrument Serial number		Silcher									
		Zwick Z 323	(nou)								
			25340120053		Contractory of the local division of the loc	North States	C. S.				
		H2932-002-50430									
Test conditio	ons										
☑ HV 10		DIN EN ISO 6507-1:2018-07									
HBW		DIN EN ISO 6506-1:2015-02									
		DIN EN ISO 6508-1:2016-12									
	Test tem	peratur, if ou									
Control	280,6	280,8	0,281	235		12812	here was to				
plate	μm	μm	mm	HV		Reference:	237 HV 10				
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Demark				
no.	μm	μm	mm	HV	HV	mm	Remark				
		010.0	0.0407	100							
1	306,2 312,6	319,2 324,0	0,3127 0,3183	190 183	185		BM 1				
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							
2	297,9	297,6	0,2978	209	- Andreas		HAZ 1				
3	295,8	296,8	0,2963	211	210						
4	298,5	297,4	0,2980	209 216							
5 1	295,2 290,4	290,6 290,6	0,2929 0,2905	216			12				
2	290,4	291,8	0,2903	219			WM				
3	290,0	292.0	0,2912	219	220						
4	289,3	286,0	0,2877	224							
5	290,6	289,5	0,2901	220							
1	298,3	302,2	0,3002	206							
2	298,9	299,3	0,2991	207	209		HAZ 2				
3	294,5	297,0	0,2958	212							
4	294,7	297,6	0,2962	211							
5 1	296,6 311,8	299,3 324,6	0,2980 0,3182	209 183							
2	306,8	324,6	0,3182	189	188		BM 2				
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										
	- Contract of the second										
	Scheck										

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

\mathbb{N}			МР	Test rep AS-PPB 523 Hardness	10-08/1	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000	í	/				
Sample desc	ription	47.1 Root	ot and a second s					
Administrate	or	Silcher						
Test instrum		Zwick Z 323	(neu)	1				
			\$93607m050					
Serial numbe		H2932-002-	50430					
Test conditio	ns					and will		
U HV	10	DIN EN ISO	6507-1:201	8-07				
HBW		DIN EN ISO	6506-1:201	5-02				
HRC		DIN EN ISO	6508-1:201	6-12	and the second			
	Test tem	peratur, if out						
Control	280,6	280,8	0,281	235		128.2	la constanta	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	Kemark	
	011.0		0.0454	107				
1	311,3 307,2	318,8 318,2	0,3151 0,3127	187 190	4 1			
3	308,4	316,2	0,3127	190	189		BM 1	
4	305,9	318,0	0,3120	191				
5	307,0	318,0	0,3125	190			1	
1	295,6	292,2	0,2939	215				
2	301,4	306,0	0,3037	201	1			
3	298,5	301,6	0,3000	206	208		HAZ 1	
4	293,3	299,5	0,2964	211				
5	299,9 291,8	302,4 294,1	0,3012 0,2930	204 216				
2	291,8	294,1	0,2930	216				
3	292,2	290,4	0,2933	219	217		WМ	
4	290,4	292,0	0,2912	219				
5	290,8	292,0	0,2914	218			1	
1	295,6	298,9	0,2972	210				
2	299,1	303,2	0,3012	204				
3	299,9	300,8	0,3003	206	206		HAZ 2	
4	302,8	300,1	0,3015	204 205				
5	297,7 313,6	303,7 324,6	0,3007 0,3191	182				
2	310,9	324,8	0,3179	184			1	
3	313,4	324,4	0,3189	182	182		BM 2	
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	s measurements of L485	, item no. 47 (3)
------------------------	------------------------	-------------------

\mathbb{N}	STUTTG4	ART	MP	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)	11		XX	
Sample desc	ription	47.2 Outer	layer	11		To Park San	
Administrate	or	Silcher		-			
Test instrum		Zwick Z 323	(neu)				1
Serial numbe		H2932-002-	50430			A CANA	
Test conditio	ns						
U HV ·	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
		DIN EN ISO			53. 2. 12		
	Terttom	peratur, if ou					
	280,6	280,8	0,281	235		7.52009	Terrare and the second
Control	280,6 µm	280,8 µm	0,281 mm	Z35 HV		Reference:	237 HV 10
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	
no.	μm	μm	mm	HV	HV	mm	Remark
1	307,8	315,3	0,3116	191	187		
2	308,2	316,3	0,3123	190			
3	308,6	318,6	0,3136	189			BM 1
4	312,0	319,9	0,3159	186 181			
5	314,9 548,9	325,3 311,9	0,3201 0,4304	100	-		
2	293,5	297,3	0,2954	213			
3	302,8	303,9	0,3034	202	188		HAZ 1
4	294,1	299,7	0,2969	210			
5	294,1	294,3	0,2942	214			1
1	290,6	291,8	0,2912	219			5. 1
2	291,8	291,8	0,2918	218			
3	289,8	286,6	0,2882	223	219		WM
4	290,2	292,9	0,2915	218			
5	291,6 302,0	291,8 307,5	0,2917 0,3047	218 200			
2	298,3	307,5	0,3047	200			1
3	295,4	299,7	0,3012	204	206		HAZ 2
4	296,2	298,9	0,2975	209			
5	297,6	298,3	0,2980	209			
1	316,9	322,6	0,3198	181			
2	313,6	324,0	0,3188	182			1
3	309,3	318,6	0,3139	188	186		BM 2
4	308,4 308,9	316,3 319,0	0,3124 0,3139	190 188			4
5	300,9	519,0	0,5158	100			
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}	STUTTGA	ART	MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat graphie und enmikroskopie
Order numb	er	9039784000)	6		XIX	
Sample desc	ription	47.2 Cente	r	11			
Administrate	ne oktivoto	Silcher					
						Ser in the	1
Test instrum	ent	Zwick Z 323	(neu)				
Serial number	er	H2932-002-	50430			A	
Test conditio	ns					and the second of	
U HV	10	DIN EN ISC	6507-1:201	8-07			
		antal and case	6506-1:201				
HRC			6508-1:201				
	Test temp	peratur, if ou	tside (23+/-	5 1 C P P P P P P P P P P P P P P P P P P			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV		A STATE STATE	
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	2010/00/00/062
1	297,0	296,4	0,2967	211			
2	304,1	315,9	0,2967	193	4 F		
3	302,0	317,2	0,3096	193	195		
4	308,0	318,6	0,3133	189			BM 1
5	308,8	319,0	0,3139	188			
1	308,9	323,8	0,3163	185			
2	297,2 295,8	293,9 296,2	0,2956	212 212	204		
4	295,8	290,2	0,2900	212	204		HAZ 1
5	305,5	304,3	0,3049	199			
1	291,4	287,7	0,2896	221			
2	288,7	284,6	0,2866	226			
3	295,6	293,3	0,2944	214	218		WM
4	293,5 293,9	296,0 290,4	0,2947 0,2921	213 217			4
5	293,9	290,4	0,2921	209			
2	298,1	301,0	0,2995	207			1
3	295,4	297,8	0,2966	211	210		HAZ 2
4	304,7	303,0	0,3039	201			1
5	290,0	290,2	0,2901	220			
1	315,5 312,8	326,3 320,1	0,3209 0,3164	180 185		1	1
3	309,7	315,9	0,3104	190	189		BM 2
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)

\mathbb{N}	STUTTGA		Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie				
Order numb	er	9039784000)	and and		XX				
Sample desc	ription	47.2 Root	2 Root							
Administrat	or	Silcher								
Test instrum		0.742.64.64.64	Zwick Z 323 (neu)							
Serial numbe			1 2000/0011	1-03						
		H2932-002-	50430			A COURSE				
Test conditio	ons									
U HV	10	DIN EN ISO	6507-1:201	8-07						
HBW		DIN EN ISO	6506-1:201	5-02						
			6508-1:201							
	Test tem	peratur, if ou								
Control	280,6	280,8	0,281	235		19280	Deservation of			
plate	280,6 µm	200,0 μm	0,201 mm	HV		Reference:	237 HV 10			
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in				
no.	μm	μm	mm	HV	HV	mm	Remark			
1	312,2	320,5	0,3163	185	187					
2	309,7 309,1	320,7 320,9	0,3152 0,3150	187 187						
4	309,1	320,9	0,3130	187			BM 1			
5	308,2	318,4	0,3133	189						
1	296,2	301,4	0,2988	208			1			
2	299,1	303,5	0,3013	204			1			
3	301,0	302,0	0,3015	204	204		HAZ 1			
4	303,3	304,9	0,3041	201						
5	299,9	300,3	0,3001	206						
1	292,9	291,6	0,2923	217						
2	290,4	292,2	0,2913	219	217		WM			
3	291,6	292,5 291,2	0,2920	217 217	217		V V I V I			
4	292,9 293,1	291,2	0,2920 0,2938	217			1			
5	302,8	299,7	0,3013	204						
2	297,4	298,9	0,2982	209			1			
3	300,1	300,1	0,3001	206	206		HAZ 2			
4	298,7	300,5	0,2996	207			1			
5	299,1	301,6	0,3003	206						
1	304,9	313,8	0,3094	194			4			
2	308,0 307,0	315,1 321,7	0,3116 0,3144	191 188	190		BM 2			
4	310,1	318,6	0,3144	188	190					
5	308,4	317,8	0,3131	189						
Date:	06.11.22									
Tester:	Scheck									
I PERSONAL PROPERTY.	SCNECK									

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

Ob anni a channa a citian	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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 $^{\circ}\mathrm{C}$

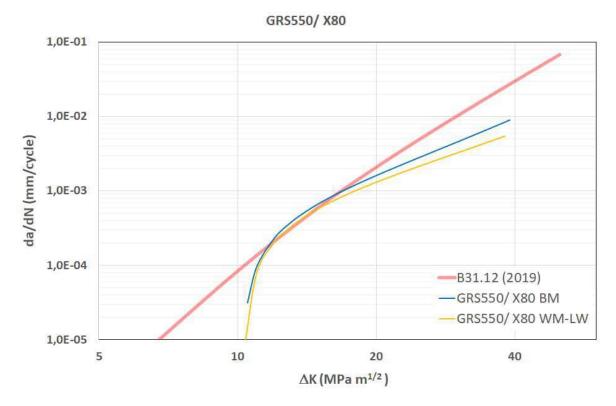


Figure 3.107: Crack growth GRS550/X80

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.

\mathbb{N}		IRT	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)	-			-	
Sample desc	intion	5.1; Outer layer						
Administrato		Silcher					- A	
			1				- En allen	
Test instrum	ent	Zwick Z 323	(neu)					
Serial numbe	er	H2932-002-	50430					
Test conditio	ns					CANE AND		
U HV 1	10	DIN EN ISO	6507-1:201	8-07	and a little		and the second s	
		DIN EN ISO			and the second		1	
HRC		DIN EN ISO						
	Test temp	peratur, if ou	tside (23+/	-5) *C				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
plate	μm	μm	mm	HV			20111110	
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	2310/02099/054	
1	292,0	300,6	0,2963	211				
2	289,3	302,8	0,2963	212	213			
3	283,9	296,2	0,2901	220				
4	290,6	299,7	0,2952	213			BM 1	
5	293,9	304,7	0,2993	207		1		
1	295,0	294,0	0,2945	214				
2	290,2	294,7	0,2925	217				
3	293,1	291,2	0,2921	217	217		HAZ 1	
4	286,4	295,6	0,2910	219				
5	289,5	294,9	0,2922	217				
1	280,0	277,7	0,2789	238				
2	281,7	283,7	0,2827	232 239	238		1.0.16.4	
3	279,6 274,4	277,5 273,8	0,2785 0,2741	239	230		WM	
4	283,3	273,8	0,2741	233				
1	286,6	293,5	0,2024	233				
2	286,0	292,5	0,2893	222			1	
3	292,1	288,9	0,2905	220	220	1	HAZ 2	
4	292,5	288,3	0,2904	220	1 1			
5	289,1	294,3	0,2917	218				
1	296,6	306,8	0,3017	204				
2	298,5	306,2	0,3023	203				
3	290,4	303,2	0,2968	210	207		BM 2	
4	292,9	303,7	0,2983	208				
5	293,3	303,0	0,2982	209				
Date:	06.11.22		I					

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

\mathbb{N}		RT	A 15.5.5 Hz	Test rep AS-PPB 523 Hardness	0-08/1	Metallo	e ferat ographie und enmikroskopie
Order numb	er	9039784000)		-		main
Sample desc	ription	5.1; Center	6				
Administrate		Silcher		5.600			And see a
Test instrum		Zwick Z 323	(nou)	T-S-S-S			
				100			
Serial numbe		H2932-002-	50430				
Test conditio	ns			1000	P		
U HV ·	10	DIN EN ISO	6507-1:201	8-07			1000
HBW		DIN EN ISO	6506-1:201	5-02	-		()
		DIN EN ISO	6508-1:201	6-12	State of the second	and the second s	
	Tertter	eratur, if ou					
	A CHOCH DUPOCO	Carles Do A Colmer, in the	STOORED STOCK OF STOP		-	1 Ultra	Townson Parameter
Control plate	280,6 µm	280,8 µm	0,281 mm	235 HV		Reference:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	
no.	μm	μm	mm	HV	HV	mm	Remark
			1.1112				
1	285,6	297,2	0,2914	218	214		_
2	287,3	296,0	0,2916	218			
3	290,0 289,1	300,8 297,9	0,2954 0,2935	213 215			BM 1
5	298,1	305,1	0,3016	204			1
1	294,1	290,8	0,2925	217			
2	290,8	292,2	0,2915	218			
3	291,6	292,2	0,2919	218	217		HAZ 1
4	293,3 293,1	291,8 291,2	0,2926 0,2921	217 217			-
1	293,1	291,2	0,2921	235		-	
2	284,6	282,7	0,2836	230			1
3	284,6	284,4	0,2845	229	232		I WM
4	282,3	279,4	0,2808	235			
5	284,6	282,3	0,2834	231			
2	295,2 297,0	292,5 289,2	0,2938 0,2931	215 216			1
3	288,3	296,2	0,2923	210	218		HAZ 2
4	290,8	288,5	0,2897	221]
5	290,4	289,1	0,2898	221			
1	301,8	308,8	0,3053	199			-
2	295,8 294,5	305,7 304,1	0,3008 0,2993	205 207	209		
4	294,5	298,5	0,2993	207	203	-	BM 2
5	286,8	295,8	0,2913	219			1
Date:	06.11.22	1		I			1

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

\mathbb{N}	STUTTG		MF	Test rep PAS-PPB 523 Hardness	10-08/1	Metallo	e ferat ographie und enmikroskopie
Order numb	er	9039784000	D	-			-
Sample desc	ription	5.1; Root			1		State .
Administrat		Silcher					
		DINEL COMPANY		12.1			A. Car
Test instrum	ent	Zwick Z 323	3 (neu)	1000			
Serial numbe	er	H2932-002-	50430	1000			
Test conditio	ns			1000			
☑ HV 10		DIN EN ISC	6507-1:201	8-07	- All	NV IIE	
HBW		DIN EN ISC	6506-1:201	5-02		S I della	
HRC		DIN EN ISC	6508-1:201	6-12	and the second second	A DECEMPTOR OF THE OWNER	
	Test tom	peratur, if ou	SALATINE AND SELEC	ATTIN TO:			
-	A CHOOM SPACE	Carles Contraction in the	BUDDOC DU MORECUPI			10000	Decomposition of the
Control	280,6	280,8	0,281	235 HV		Reference:	237 HV 10
	μm	μm	mm		Manualus	Distance in	
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
10.	hun	pm					
1	292,2	300,1	0,2962	211	211		
2	291,6	300,1	0,2959	212			1
3	292,7	299,7	0,2962	211			BM 1
4	292,3	298,7	0,2955	212	224 Car (117)		
5	294,5	299,3	0,2969	210			
1	279,8	284,0	0,2819	233			HAZ 1
2	291,8	290,4	0,2911	219			
3	295,0	289,8	0,2924	217	222		
4	296,2	289,6	0,2929	216 227			
5	288,5 285,2	283,3 277,3	0,2859 0,2813	227		1	7
2	200,2	278,1	0,2013	234			
3	278,8	276,9	0,2778	240	243		WM
4	272,5	268,8	0,2707	253			1
5	275,2	270,7	0,2729	249			1
1	276,7	270,9	0,2738	247		<u></u>	
2	274,8	275,2	0,2750	245	10000		
3	278,5	284,8	0,2817	234	235		HAZ 2
4	286,2	288,7	0,2875	224			ł
5	286,0	286,2	0,2861	227			
1	297,2	302,4	0,2998	206			4
	295,2	302,6	0,2989	208	010	-	
2	288,7	302,6	0,2957	212	210		BM 2
3		300,1	0,2956	212			•
	291,0 288,9	299,7	0,2943	214			

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

Order numbe Sample descri Administrato Test instrume Serial numbe		9039784000			test	Elektrone	graphie und anmikroskopie
Administrato Test instrume	iption)	-	-		
Test instrume		5.2; Outer I	ayer		1.100		Sec. 1
Test instrume	r	Silcher	and a second provide the		an A		
		an and the spectrum	9. <i>16</i> .				
Serial number	ent	Zwick Z 323	(neu)				
	r	H2932-002-	50430				
Test condition	15				63		
⊡ HV 1	0	DIN EN ISO	6507-1:201	8-07			and the second
	-	DOL WAR STILLOUDS	6506-1:201			11517	
		atom of the		and the second s	The second	Company of the local division of the local d	
HRC		574507672M24635427	6508-1:201	549.574.			
	Test tem	peratur, if ou	STOOLE IN MARKED IN	-5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	d₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	10101030000
1	291,2	305,4	0,2983	208		1	
2	294,3	304,7	0,2995	200			1
3	292,2	304,3	0,2983	208	207	1	BM 1
4	292,0	303,5	0,2978	209	256-69		
5	297,6	306,2	0,3019	203			
1	296,8	298,9	0,2979	209		l.	1
2	297,7	289,8	0,2937	215	210	4	HAZ 1
3	289,0 290,0	294,8 290,8	0,2919	218 220	216	6 	
4	290,0	290,8	0,2904	219			
1	280,2	282,7	0,2911	234			,
2	283,5	282,9	0,2832	231		C	
3	283,9	281,3	0,2826	232	234	1	WM
4	282,1	276,5	0,2793	238			
5	281,7	281,9	0,2818	234		1	
1	296,0	291,6	0,2938	215			
2	291,6	293,7	0,2927	217	010	1	HAZ 2
3	288,5	292,2 287,5	0,2904 0,2906	220 220	219	1	
4	293,7	287,5	0,2906	220			1
1	299,7	305,5	0,3026	202			
2	297,2	308,5	0,3029	202			
3	292,9	302,8	0,2978	209	207		BM 2
4	292,9	302,4	0,2976	209			1
5	289,6	299,3	0,2944	214			
Date: 0	6.11.22						

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

\mathbb{N}	STUTTG		MF	Test rep AS-PPB 523 Hardness	10-08/1	Metallo	e ferat ographie und enmikroskopie
Order numb	er	9039784000)	-	-		
Sample desc	ription	5.2; Center					Allela
Administrate		Silcher			A.		
			15. SDN				
Test instrum	ent	Zwick Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ns				1		
U HV ·	10	DIN EN ISC	6507-1:201	8-07			itor.
HBW		DIN EN ISC	6506-1:201	5-02	the second second		
		tel hannes	6508-1:201		State Support	and the second division of the second divisio	and the second
	-						
	A CHOORE DROPPING	peratur, if ou					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation	d,	d₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	1010100703086
	005.0	205.0	0.0004	200			
1	285,0	295,8 301,8	0,2904 0,2935	220 215			-
3	290.8	304,3	0.2975	209	212	-	BM 1
4	293,3	302,8	0,2981	209			
5	293,3	303,9	0,2986	208			
1	290,4	293,9	0,2921	217			
2	286,6	282,9	0,2848	229			
3	284,4	284,6	0,2845	229	221	-	HAZ 1
4	292,7 293,1	295,8 292,7	0,2942	214 216			
1	293,1	292,7	0,2929	236		1	-
2	284,4	281,3	0.2805	230		-	-
3	282,3	282,9	0,2826	232	234	97. - 1	l wм
4	280,4	278,3	0,2794	238	n Gerficht i	el.	1
5	283,3	278,8	0,2810	235			
1	294,3	292,7	0,2935	215			-
2	289,5	290,8	0,2902	220	12.23	-	
3	286,4	291,6	0,2890	222	221	-	HAZ 2
4	290,6 285,4	286,0 288,9	0,2883 0,2872	223 225		R	4
5	295,2	307,6	0,2072	225			
2	296,6	304,3	0,3005	204			1
3	293,5	306,6	0,3000	206	207		BM 2
4	292,9	304,5	0,2987	208	100000]
5	289,8	301,0	0,2954	213			-
			d			d	
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}	STUTTG	ART	Test report MPAS-PPB 52310-08/1 Hardness test			Metallo	graphie und mmikroskopie
Order numb	er	9039784000)	-			-
Sample desc	ription	5.2; Root			A A		61
Administrate	or.	Silcher		1000			
		SANT LENGT					
Test instrum	ent	Zwick Z 323	(neu)	100			
Serial numbe	er	H2932-002-	50430				
Test conditio	ns			12.20	1		
⊡ HV 1	10	DIN EN ISO	6507-1:201	9.07	Contraction of the second s		-
	10	50000000000000000000000000000000000000	1239131 122323	-	and the second second		
HBW		DIN EN ISC	6506-1:201	5-02	-	Constant of the local division of	A CONTRACTOR OF
HRC		DIN EN ISC	6508-1:201	6-12		and the second second	and the second
	Test tem	peratur, if ou	tside (23+/-	5) °C			
Control	280,6	280,8	0,281	235		P-f-	
plate	μm	μm	mm	HV	Keterence:		237 HV 10
Indentation	d,	d ₂	dm	Hardness	Mean value	Mean value Distance in	
no.	μm	μm	mm	HV	HV	mm	Remark
1	293,1	302,0	0,2975	209			
2	293,1	302,0	0,2975	209			3
3	295,4	304,3	0,2998	207	209	-	BM 1
4	291.4	299,9	0,2957	212			
5	293,3	302,0	0,2977	209			
1	282,3	288,1	0,2852	228			
2	276,1	283,1	0,2796	237			
3	285,6	291,4	0,2885	223	227		HAZ 1
4	283,7	292,2	0,2880	224			
5	287,1	290,8	0,2889	222			
1	282,9	284,0	0,2834	231			
2	279,2	276,5	0,2778	240	045		WM
3	276,3	275,8	0,2761	243 253	245		
4	270,2	270,9	0,2706				1
5	269,4 278,8	269,6	0,2695	255 240			
2	263,2	268,8	0,2660	262			
3	275.0	276,5	0,2758	244	244		HAZ 2
4	274,8	279,2	0,2770	242	1000		
5	282,1	284,2	0,2831	231			
1	298,5	306,2	0,3023	203			-
2	296,4	305,7	0,3011	205			
3	294,3	303,9	0,2991	207	208		BM 2
4	288,3	299,9	0,2941	214			
5	293,3	303,5	0,2984	208			-
	06.11.22 Scheck			1			

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

	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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 _{JIc} [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

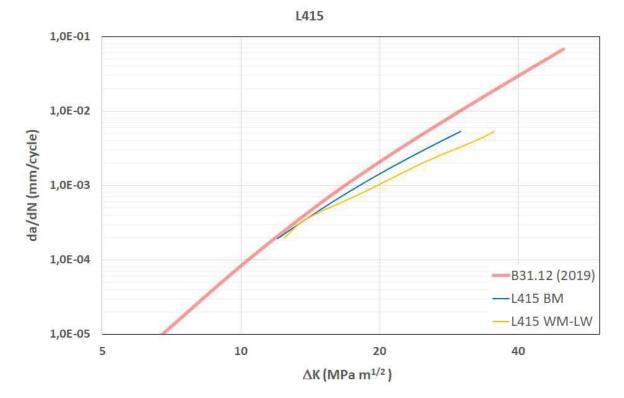


Figure 3.114: Crack growth L415

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

Ob anni a al a anna a aiti a n	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

 $^{^{\}rm 23}$ Sample form as per ASTM A 370 transverse at 0°C

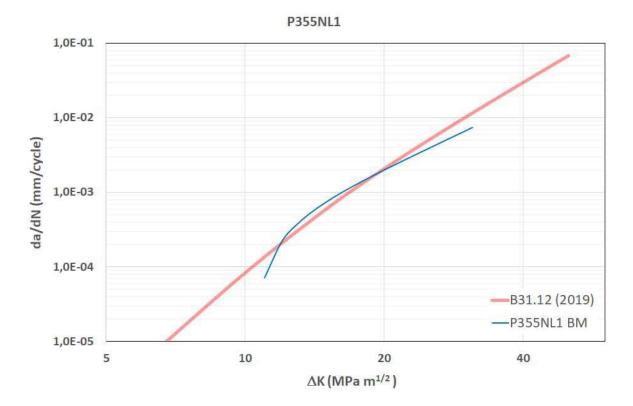


Figure 3.115: Crack growth in P355 NL1

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

Ob anni a sharan a siti a n	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition	3.822				0.0038			
	Ni	V	Ti	Nb				

Table 3.86: Fracture toughness of GJS400

Material	Location	Item no.	K_{Jlc} [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.

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

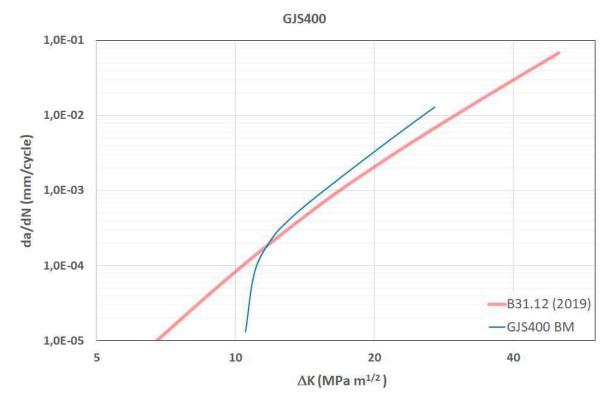


Figure 3.116: Crack growth GJS400

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 (201	7)	
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	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

 $^{^{25}}$ Notched-bar impact test as per DIN EN ISO 148-1 at -60 °C, form: CV

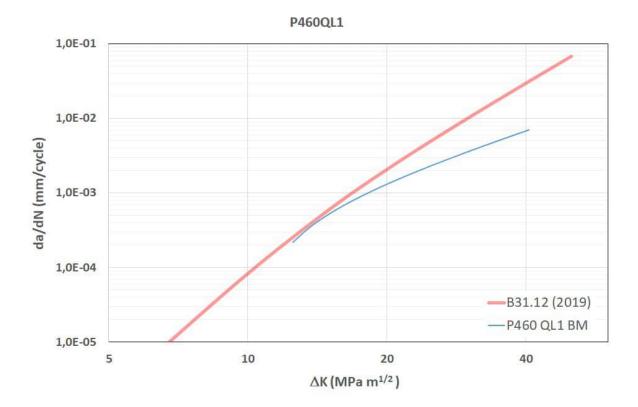


Figure 3.117: Crack growth P460 QL1

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

Chaminal	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

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 $^\circ\text{C}$

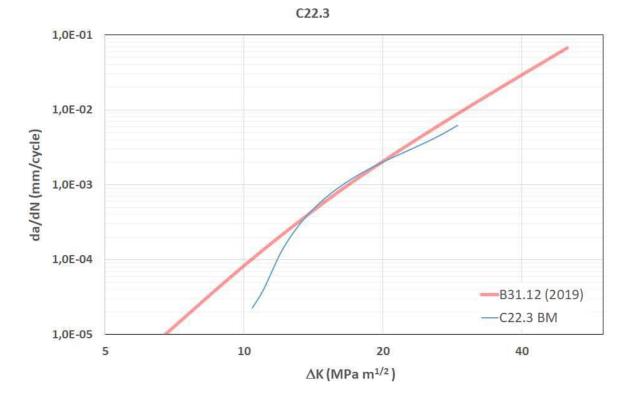


Figure 3.118: Crack growth C22.3

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

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

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

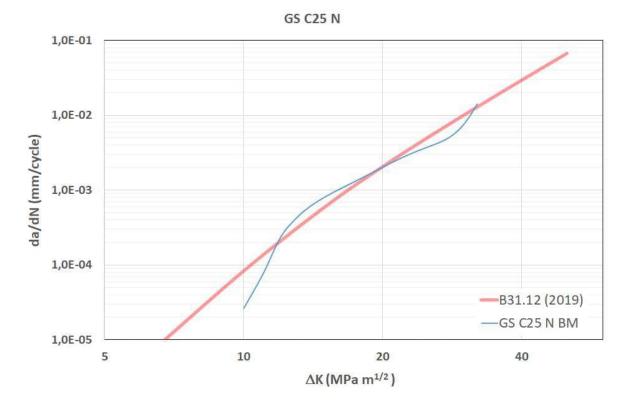


Figure 3.119: Crack growth GS C25 N

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

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
Chemical composition [%]	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_{JIc} [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.

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

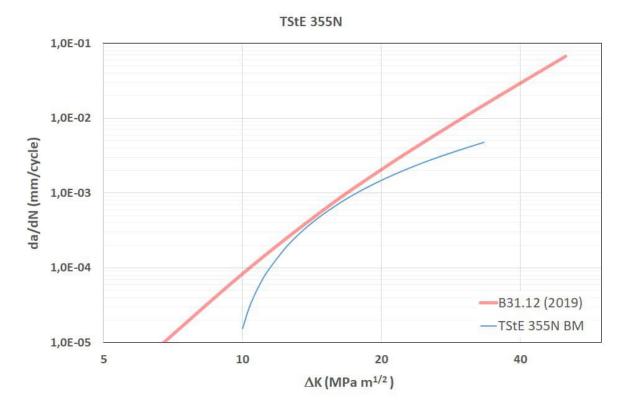


Figure 3.120: Crack growth TStE 355N

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.

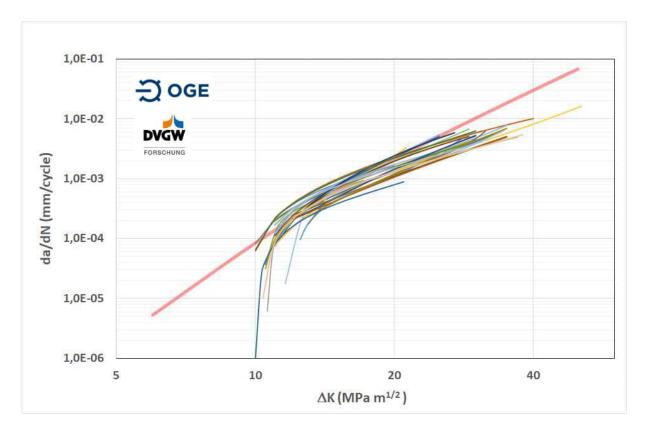


Figure 4.1: Established crack growth of the investigated materials in hydrogen (100 bar, R = 0.5)

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.

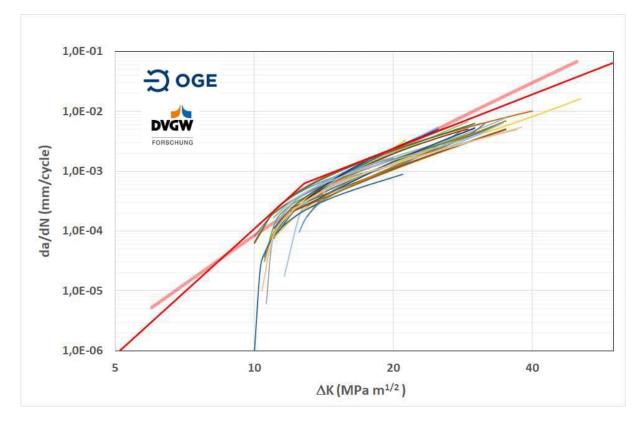


Figure 4.2: Conservative description of the established crack growth in hydrogen for $p_{\rm H2}$ = 100 bar and R = 0.5

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 $\Delta K \leq 12.851 MPa\sqrt{m}$	$\frac{da}{dN} = 1.1 \cdot 10^{-11} \cdot \Delta K^7$
for $\Delta K \ge 12.851 MPa\sqrt{m}$	$\frac{da}{dN} = 3 \cdot 10^{-7} \cdot \Delta K^3$

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

4.2 Crack Growth Law Depending on Hydrogen Pressure pH2

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.

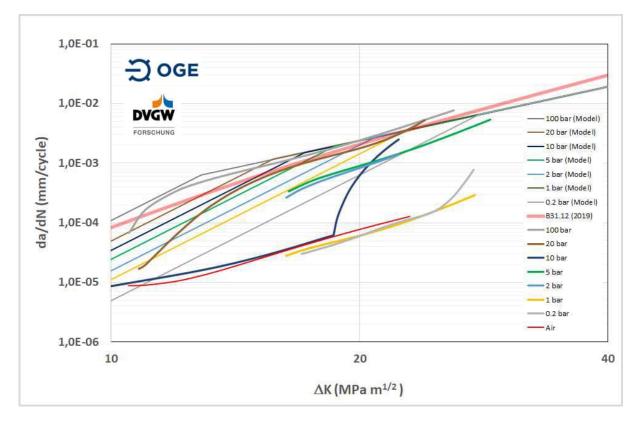


Figure 4.3: Crack growth in hydrogen for different hydrogen pressures and bilinear model (St35, item no. 25ff at R = 0.5)

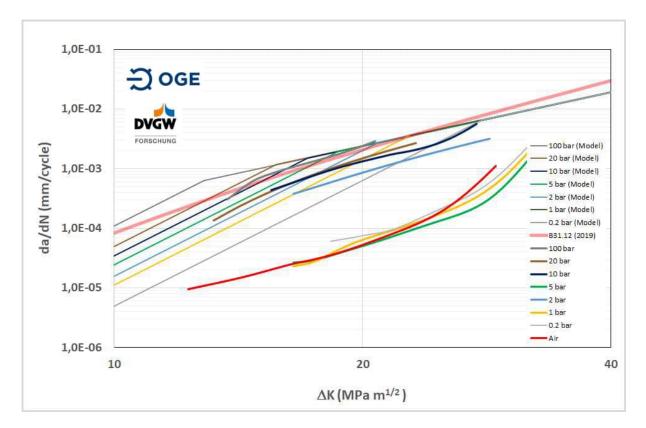


Figure 4.4: Crack growth in hydrogen for different hydrogen pressures and bilinear model (St35, item no. 41 at R = 0.5)

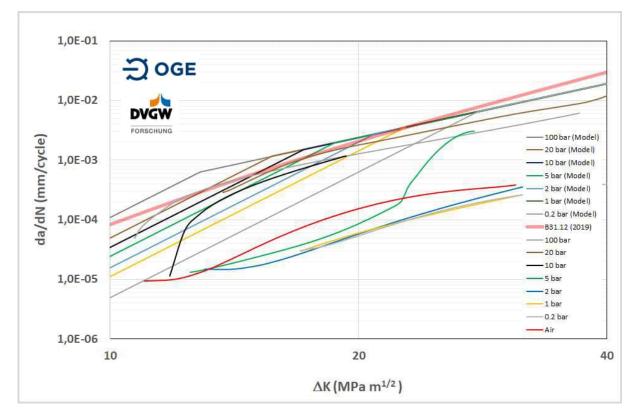


Figure 4.5: Crack growth in hydrogen for different hydrogen pressures and bilinear model (L485, item no. 32ff at R = 0.5)

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 H₂-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 $\Delta K > 22$ 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 $\Delta K \leq [3.6667 \cdot 10^{-6} \sqrt{p_{H2}}]^{-0.25} MPa\sqrt{m}$ for $\Delta K \geq [3.6667 \cdot 10^{-6} \sqrt{p_{H2}}]^{-0.25} MPa\sqrt{m}$ $\frac{da}{dN} = 1.1 \cdot 10^{-12} \cdot \Delta K^7 \cdot \sqrt{p_{H_2}}$ $\frac{da}{dN} = 3 \cdot 10^{-7} \cdot \Delta K^3$

 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.

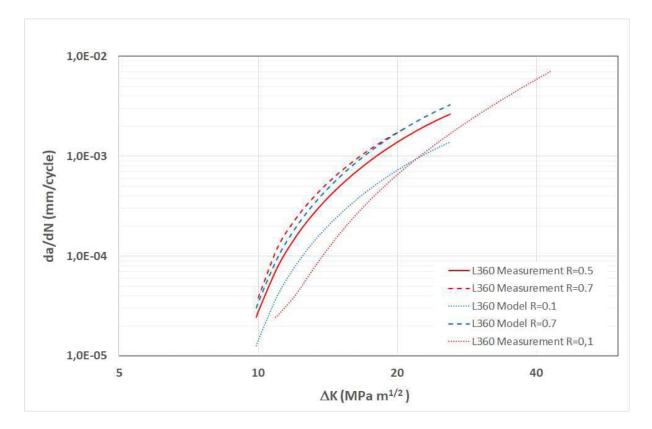


Figure 4.6: Calculated and measured impact of the R value on crack growth behaviour (L360, R = 0.1, R = 0.5, R = 0.7 p_{H2} =100 bar)

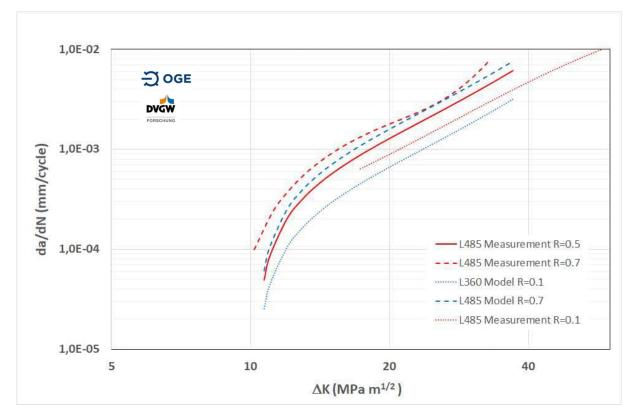


Figure 4.7: Calculated and measured impact of the R value on crack growth behaviour (L485, R = 0.1, R = 0.5, R = 0.7 p_{H2} =100 bar)

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.

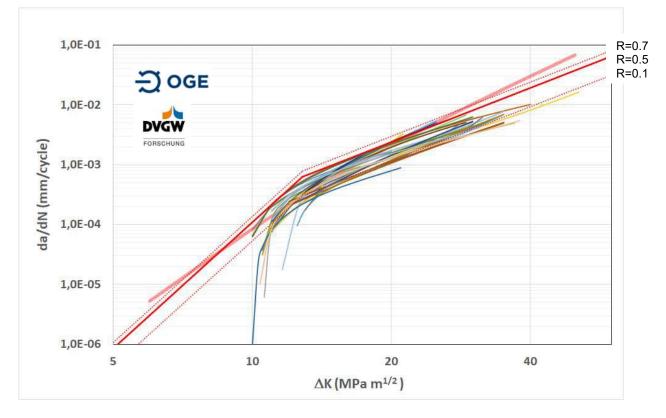


Figure 4.8: Bilinear crack growth law for R=0.1, R=0.5 and R=0.7 (p_{H2} =100 bar)

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

for $\Delta K \leq [3.6667 \cdot 10^{-6} \sqrt{p_{H2}}]^{-0.25} MPa\sqrt{m}$ for $\Delta K \geq [3.6667 \cdot 10^{-6} \sqrt{p_{H2}}]^{-0.25} MPa\sqrt{m}$ for $\Delta K \geq [3.6667 \cdot 10^{-6} \sqrt{p_{H2}}]^{-0.25} MPa\sqrt{m}$ $\frac{da}{dN} = 1.2 \cdot 10^{-7} \cdot (1 + 3 \cdot R) \cdot \Delta K^{3}$ PH2 [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_{lc} 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_{lc} = 55 MPa m^{1/2}) is also indicated.

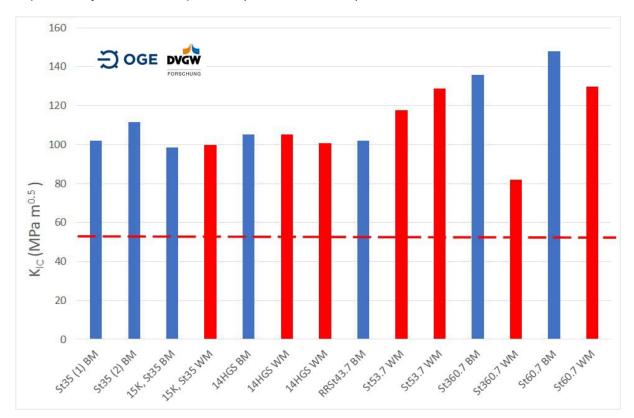
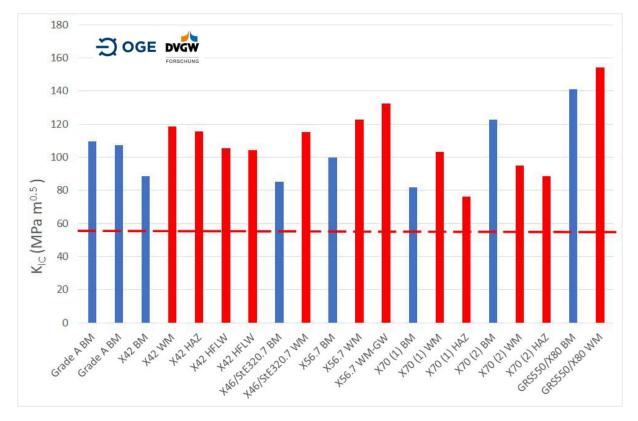
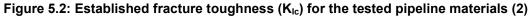


Figure 5.1: Established fracture toughness (K_{lc}) for the tested pipeline materials (1)





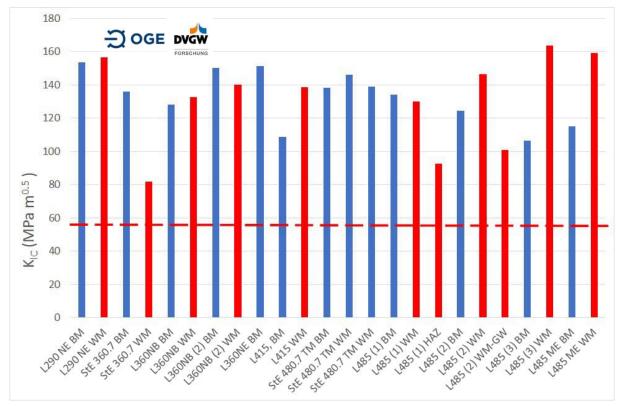


Figure 5.3: Established fracture toughness (K_{Ic}) for the tested pipeline materials (3)

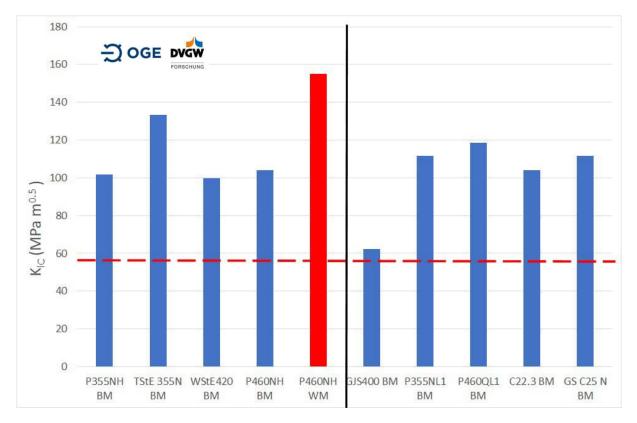
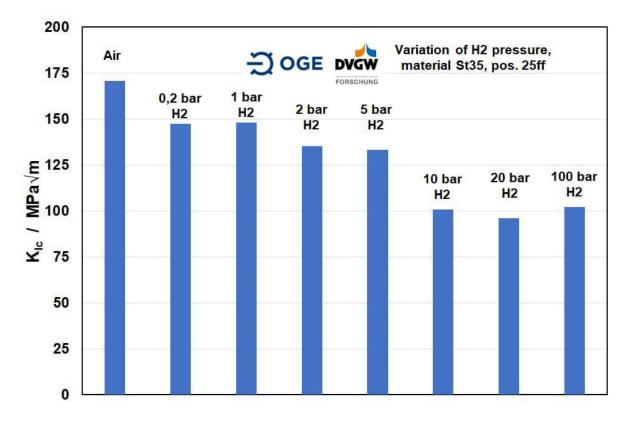


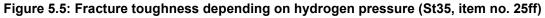
Figure 5.4: Established fracture toughness (K_{lc}) for line pipe materials (plants) and valves (pressure vessels)

All investigated samples complied with the minimum requirement for fracture toughness $K_{lc} \ge 55 \text{ MPam}^{\frac{1}{2}}$ 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 ($K_{Ic} \cong 170 \text{ MPa m}^{1/2}$) were established in air (0 bar H₂). 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 $K_{Ic} \cong 100 \text{ MPam}^{1/2}$ at hydrogen pressures of $p_{H2} = 10 - 20$ bar. If hydrogen pressure is further increased, this fracture toughness remains approximately constant.





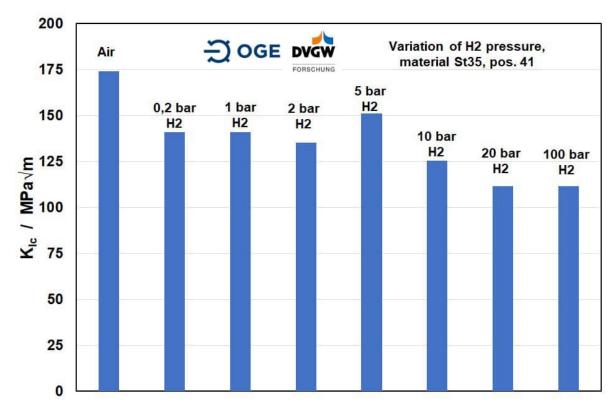


Figure 5.6: Fracture toughness depending on hydrogen pressure (St35, item no. 41)

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_{lc} \geq 55 Mpam^{0.5} was always considerably exceeded.

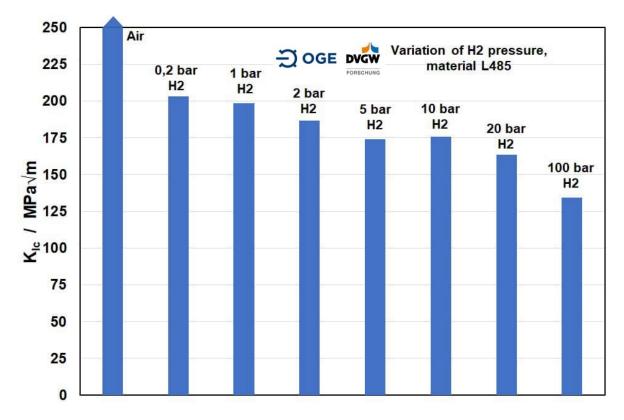


Figure 5.7: Fracture toughness depending on hydrogen pressure (L485)

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 $p_{H2} \leq 1$ 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

- [1] DVGW, DVGW Technical Note G 409 (M) : Conversion of High Pressure Gas Steel Pipelines for a Design Pressure of more than 16 bar for Transportation of Hydrogen, 2020.
- [2] DVGW, DVGW Technical Rule G 463 (A) : High Pressure Gas Steel Pipelines for a Design Pressure of more than 16 bar; Design and Construction, 2021.
- [3] ASME, ASME B31.12:2019 Hydrogen Piping and Pipelines.
- [4] ASTM International, ASTM E1820-20 Standard Test Method for Measurement of Fracture Toughness.
- [5] ASTM International, ASTM E647-13a Standard Test Method for Measurement of Fatigue Crack Growth Rates.
- [6] DVGW, DVGW Technical Rule G 410 (A) : Registration of Asset Inventory and Incident Data of Gas Infrastructures, 2017.
- [7] R. L. Amaro, R. M. White, C. P. Looney, E. S. Drexler und A. J. Slifka, *Development of a Model for Hydrogen-Assisted Fatigue Crack Growth of Pipeline Steel*, Journal of Pressure Vessel Technology, 2018.
- [8] C. S. Marchi und . J. A. Ronevich, *Fatigue and Fracture of Pipeline Steels in High-Pressure Hydrogen Gas,* Las Vegas, Nevada, 2022.
- [9] ASME Boiler & Pressure Vessel Code, Alternative Rules for Construction of High-Pressure Vessels; Rules for Construction of Pressure Vessels, ASME International, 2010.

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 _{Jlc}	Fracture toughness calculated from J_{lc} 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	-
$C \Delta K^m$	Paris equation	mm/load cycle
J	J integral	J/mm ²
А	Sample cross section	mm ²
∆a	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

10 List of Figures

Figure 2.1: Cross-section of a submerged arc-welded steel pipe	4
Figure 2.2: Sample geometry for static tests (left) and cyclical tests (right)	5
Figure 2.3: Removal of samples from a spiral welded pipe	5
Figure 2.4: Servohydraulic testing system of MPA Stuttgart using an integrated hydrogen	
autoclave	6
Figure 2.5: Increase in cyclical stress intensity ∆K due to crack growth	7
Figure 2.6: Crack depth and stress intensities K_{min} , K_{max} and ΔK depending on the number	
cycles during testing	
Figure 2.7: Schematic representation of crack growth depending on cyclical stress intensit	
ΔΚ	-
Figure 2.8: Load-crack opening diagram (F-COD)	
Figure 2.9: Crack resistance curve (JR curve)	
Figure 3.1: Investigated materials	
Figure 3.2: Material classes in pipeline construction	
Figure 3.3: Crack growth L290 NE	
Figure 3.4: Hardness measurements of L290 NE (1)	
Figure 3.5: Hardness measurements of L290 NE (2)	
Figure 3.6: Hardness measurements of L290 NE (3)	
Figure 3.7: Hardness measurements of L290 NE (4)	
Figure 3.8: Hardness measurements of L290 NE (5)	
Figure 3.9: Hardness measurements of L290 NE (6)	
Figure 3.10: Crack growth 5L Grade A	
Figure 3.11: Crack growth St35	
Figure 3.12: Crack growth St35 at different pressures	
Figure 3.13: Crack growth St35 (item no. 41) at different pressures	
Figure 3.14: Crack growth 15k (St35)	
Figure 3.15: Hardness measurements of 15k (St35) (1)	
Figure 3.16: Hardness measurements of 15k (St35) (2)	
Figure 3.17: Hardness measurements of 15k (St35) (3)	
Figure 3.18: Hardness measurements of 15k (St35) (4)	
Figure 3.19: Hardness measurements of 15k (St35) (5)	
Figure 3.20: Hardness measurements of 15k (St35) (6)	
Figure 3.21: Hardness measurements of 15k (St35) (7)	
Figure 3.22: Crack growth X42	
Figure 3.23: Hardness measurements of X42 (1)	
Figure 3.24: Hardness measurements of X42 (2)	
Figure 3.25: Hardness measurements of X42 (3)	
Figure 3.26: Hardness measurements of X42 (4)	
Figure 3.27: Crack growth RRSt43.7	
Figure 3.28: Crack growth P355 NH	
Figure 3.29: Crack growth L360 NE	
Figure 3.30: Crack growth L360NB	
Figure 3.31: Crack growth X46 / StE320.7	
Figure 3.32: Crack growth StE360.7	
Figure 3.33: Hardness measurements of StE360.7 (1)	
Figure 3.34: Hardness measurements of StE360.7 (2)	

Figure 3.35: Hardness measurements of StE360.7 (3)	
Figure 3.36: Hardness measurements of StE360.7 (4)	
Figure 3.37: Crack growth StE480.7 TM	
Figure 3.38: Crack growth L360 NB.	
Figure 3.39: Hardness measurements of L360 NB (1)	
Figure 3.40: Hardness measurements of L360 NB (2)	
Figure 3.41: Hardness measurements of L360 NB (3)	
Figure 3.42: Hardness measurements of L360 NB (4)	
Figure 3.43: Crack growth 14HGS	
Figure 3.44: Hardness measurements of 14HGS (1)	
Figure 3.45: Hardness measurements of 14HGS (2)	
Figure 3.46: Hardness measurements of 14HGS (3)	
Figure 3.47: Hardness measurements of 14HGS (4)	
Figure 3.48: Hardness measurements of 14HGS (5)	
Figure 3.49: Hardness measurements of 14HGS (6)	
Figure 3.50: Hardness measurements of 14HGS (7)	
Figure 3.51: Hardness measurements of 14HGS (8)	
Figure 3.52: Hardness measurements of 14HGS (9)	
Figure 3.53: Hardness measurements of 14HGS (10)	
Figure 3.54: Crack growth WStE 420	
Figure 3.55: Crack growth St53.7	
Figure 3.56: Hardness measurements of St53.7 (1)	
Figure 3.57: Hardness measurements of X56.7 (2)	84
Figure 3.58: Hardness measurements of X56.7 (3)	85
Figure 3.59: Hardness measurements of X56.7 (4)	86
Figure 3.60: Crack growth X56.7	88
Figure 3.61: Hardness measurements of X56.7 (1)	89
Figure 3.62: Hardness measurements of X56.7 (2)	90
Figure 3.63: Hardness measurements of X56.7 (3)	
Figure 3.64: Hardness measurements of X56.7 (4)	92
Figure 3.65: Hardness measurements of X56.7 (5)	93
Figure 3.66: Hardness measurements of X56.7 (6)	
Figure 3.67: Hardness measurements of X56.7 (7)	
Figure 3.68: Hardness measurements of X56.7 (8)	
Figure 3.69: Hardness measurements of X56.7 (9)	
Figure 3.70: Hardness measurements of X56.7 (10)	
Figure 3.71: Crack growth St60.7	
Figure 3.72: Hardness measurements of St60.7 (1)	
Figure 3.73: Hardness measurements of St60.7 (2)	
Figure 3.74: Hardness measurements of St60.7 (3)	
Figure 3.75: Hardness measurements of St60.7 (4)	
Figure 3.76: Crack growth P460 NH	
Figure 3.77: Hardness measurements of P460 NH (1)	
Figure 3.78: Hardness measurements of P460 NH (2)	
Figure 3.79: Hardness measurements of P460 NH (3)	
Figure 3.80: Hardness measurements of P460 NH (4)	
Figure 3.81: Hardness measurements of P460 NH (5)	
Figure 3.82: Crack growth L485 (item no. 17)	
Figure 3.83: Crack growth L485 at different pressures	
1 yure 0.00. Orack growth 2400 at unicient pressures	/

Figure 3.84: Crack growth L485 (item no. 43; tempered)	.118
Figure 3.85: Crack growth L485 (hardened)	.119
Figure 3.86: Hardness measurements of L485, item no. 17 (1)	.120
Figure 3.87: Hardness measurements of L485, item no. 17 (2)	.121
Figure 3.88: Hardness measurements of L485, item no. 17 (3)	.122
Figure 3.89: Hardness measurements of L485, item no. 17 (4)	
Figure 3.90: Hardness measurements of L485, item no. 40 (5)	
Figure 3.91: Hardness measurements of L485, item no. 40 (6)	
Figure 3.92: Crack growth in L485 (item no. 2)	
Figure 3.93: Hardness measurements of L485, item no. 2 (1)	
Figure 3.94: Hardness measurements of L485, item no. 2 (2)	
Figure 3.95: Hardness measurements of L485, item no. 2 (3)	
Figure 3.96: Hardness measurements of L485, item no. 2 (4)	
Figure 3.97: Hardness measurements of L485, item no. 2 (5)	
Figure 3.98: Hardness measurements of L485, item no. 2 (6)	
Figure 3.99: Crack growth L485	
Figure 3.100: Crack growth L485 (batch 2)	
Figure 3.101: Hardness measurements of L485, item no. 47 (1)	
Figure 3.102: Hardness measurements of L485, item no. 47 (2)	
Figure 3.103: Hardness measurements of L485, item no. 47 (3)	
Figure 3.104: Hardness measurements of L485, item no. 47 (4)	
Figure 3.105: Hardness measurements of L485, item no. 47 (5)	
Figure 3.106: Hardness measurements of L485, item no. 47 (6)	
Figure 3.107: Crack growth GRS550/X80	
Figure 3.108: Hardness measurements of GRS550/X80 (1)	
Figure 3.109: Hardness measurements of GRS550/X80 (2)	
Figure 3.110: Hardness measurements of GRS550/X80 (3)	
Figure 3.111: Hardness measurements of GRS550/X80 (4)	
Figure 3.112: Hardness measurements of GRS550/X80 (5)	
Figure 3.113: Hardness measurements of GRS550/X80 (6)	
Figure 3.114: Crack growth L415	
Figure 3.115: Crack growth in P355 NL1	
Figure 3.116: Crack growth GJS400	
Figure 3.117: Crack growth P460 QL1	
Figure 3.118: Crack growth C22.3	
Figure 3.119: Crack growth GS C25 N	
Figure 3.120: Crack growth TStE 355N	
Figure 4.1: Established crack growth of the investigated materials in hydrogen (100 bar, F	
Figure 4.2: Conservative description of the established crack growth in hydrogen for p_{H_2} = 100 bar and R = 0.5	
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)	.168
Figure 4.5: Crack growth in hydrogen for different hydrogen pressures and bilinear model	
(L485, item no. 32ff at R = 0.5)	.168
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)	.170

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)170
Figure 4.8: Bilinear crack growth law for R=0.1, R=0.5 and R=0.7 (p_{H2} =100 bar)171
Figure 5.1: Established fracture toughness (K_{Ic}) for the tested pipeline materials (1)172
Figure 5.2: Established fracture toughness (K_{Ic}) for the tested pipeline materials (2)173
Figure 5.3: Established fracture toughness (K_{Ic}) for the tested pipeline materials (3)173
Figure 5.4: Established fracture toughness (K_{lc}) for line pipe materials (plants) and valves
(pressure vessels)174
Figure 5.5: Fracture toughness depending on hydrogen pressure (St35, item no. 25ff)175
Figure 5.6: Fracture toughness depending on hydrogen pressure (St35, item no. 41)175
Figure 5.7: Fracture toughness depending on hydrogen pressure (L485)176

11 List of Tables

Table 3.1: Characteristics for L290 NE	
Table 3.2: Chemical composition of L290 NE	14
Table 3.3: Fracture toughness of L290 NE	14
Table 3.4: Characteristics of 5L Grade A	22
Table 3.5: Chemical composition of 5L Grade A	22
Table 3.6: Fracture toughness of 5L Grade A	
Table 3.7: Characteristics of St35	24
Table 3.8: Chemical composition of St35	24
Table 3.9: Fracture toughness of St35	24
Table 3.10: Characteristics of St35	26
Table 3.11: Chemical composition of St35	27
Table 3.12: Fracture toughness of St35	
Table 3.13: Characteristics of 15k (St35)	28
Table 3.14: Chemical composition of 15k (St35)	28
Table 3.15: Fracture toughness of 15k (St35)	28
Table 3.16: Characteristics of X42	37
Table 3.17: Chemical composition of X42	37
Table 3.18: Fracture toughness of X42	37
Table 3.19: Characteristics of RR St43.7	43
Table 3.20: Chemical composition of RR St43.7	43
Table 3.21: Fracture toughness of RR St43.7	
Table 3.22: Characteristics of P355 NH/NL2	
Table 3.23: Chemical composition of P355 NH/NL2	45
Table 3.24: Fracture toughness of P355 NH/NL2	
Table 3.25: Characteristics of L360NE	
Table 3.26: Chemical composition of L360NE	47
Table 3.27: Fracture toughness of L360NE	
Table 3.28: Characteristics of L360NB	
Table 3.29: Chemical composition of L360NB	49
Table 3.30: Fracture toughness of L360NB	
Table 3.31: Characteristics of X46 / StE320.7	51
Table 3.32: Chemical composition of X46 / StE320.7	51
Table 3.33: Fracture toughness of X46 / StE320.7	
Table 3.34: Characteristics of StE360.7	
Table 3.35: Chemical composition of StE360.7	53
Table 3.36: Fracture toughness of StE360.7	
Table 3.37: Characteristics of StE480.7 TM	59
Table 3.38: Chemical composition of StE480.7 TM	59
Table 3.39: Fracture toughness of StE480.7 TM	59
Table 3.40: Characteristics of L360 NB	
Table 3.41: Chemical composition of L360 NB	61
Table 3.42: Fracture toughness of L360 NB	61
Table 3.43: Characteristics 14HGS	
Table 3.44: Chemical composition of 14HGS	67
Table 3.45: Fracture toughness of 14HGS	
Table 3.46: Characteristics of WSTE 420	

Table 3.47: Chemical composition of WSTE 420	
Table 3.48: Fracture toughness of WSTE 420	
Table 3.49: Characteristics of St53.7	
Table 3.50: Chemical composition of St53.7	
Table 3.51: Fracture toughness of St53.7.	
Table 3.52: Characteristics of X56.7	
Table 3.53: Chemical composition of X56.7	
Table 3.54: Fracture toughness of X56.7	
Table 3.55: Characteristics of St60.7	
Table 3.56: Chemical composition of St60.7	
Table 3.57: Fracture toughness of St60.7	
Table 3.58: Characteristics P460 NH	
Table 3.59: Chemical composition of P460 NH	
Table 3.60: Fracture toughness of P460 NH	105
Table 3.61: Characteristics of X70	
Table 3.62: Chemical composition of X70	112
Table 3.63: Fracture toughness of X70	112
Table 3.64: Characteristics of L485	114
Table 3.65: Chemical composition of L485	114
Table 3.66: Fracture toughness of L485	115
Table 3.67: Characteristics of L485	126
Table 3.68: Chemical composition of L485	126
Table 3.69: Characteristics of L485 ME	133
Table 3.70: Chemical composition of L485 ME	133
Table 3.71: Fracture toughness of L485 ME	
Table 3.72: Characteristics of L485 (batch 2)	
Table 3.73: Chemical composition of L485 (batch 2)	
Table 3.74: Fracture toughness of L485 (batch 2)	135
Table 3.75: Characteristics of GRS550/X80	
Table 3.76: Chemical composition of GRS550/X80	
Table 3.77: Fracture toughness of GRS550/X80	
Table 3.78: Characteristics of L415	
Table 3.79: Chemical composition of L415	
Table 3.80: Fracture toughness of L415	
Table 3.81: Characteristics of P355 NL1	
Table 3.82: Chemical composition of P355 NL1	
Table 3.83: Fracture toughness of P355 NL1	
Table 3.84: Characteristics of GJS400	
Table 3.85: Chemical composition of GJS400	
Table 3.86: Fracture toughness of GJS400	
Table 3.87: Characteristics of P460 QL1	
Table 3.88: Chemical composition of P460 QL1	
Table 3.89: Fracture toughness of P460 QL1 Table 3.90: Characteristics of C22.3	
Table 3.91: Chemical composition of C22.3 Table 3.02: Fracture toughness of C22.3	
Table 3.92: Fracture toughness of C22.3 Table 3.92: Characteristics of CS C25 N	
Table 3.93: Characteristics of GS C25 N	
Table 3.94: Chemical composition of GS C25 N. Table 2.95: Fractive townshares of CS C25 N.	
Table 3.95: Fracture toughness of GS C25 N	161

Table 3.96: Characteristics of TStE 355N	163
Table 3.97: Chemical composition of TStE 355N	163
Table 3.98: Fracture toughness of TStE 355N	163

Imprint

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

Reprint and reproduction only permitted in original text, not as extracts.