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

Final Report

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Summary

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

As part of this project, fracture-mechanical tests were performed on a representative 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.

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1 Terms of Reference

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

So far, it was only in ASME B 31.12 [3] that these parameters were specified in an international code of practice. They specifically involve minimum fracture toughness (K_{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	0/02/1/2/5/10/20/100	
L485	BM	070.27172737107207100	
L360 NB	BM, WM		
StE 320.7	BM, GW	10 / 100	
StE 480.7 TM	BM, SAWL, GW		
L485	BM	100	01/05/07
L360	BM	100	0.1 / 0.5 / 0.7

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 (2018-09	9)
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

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

	Test rep MPAS-PPB 523 Hardness	00000000000000000000000000000000000000	Re Metallo Elektrone	e ferat ographie und enmikroskopie					
mber 9039784000									
escription 39.1; Outer laye	F 2		EV.						
ator Silebor		and a start							
Siciler									
ument Zwick Z 323 (neu	Zwick Z 323 (neu)								
nber H2932-002-50430)								
itions									
10 DIN EN ISO 6507	-1:2018-07								
DIN EN ISO 6506	-1:2015-02								
DIN EN ISO 6508	-1:2016-12								
Test temperatur, if outside	= (23+/-5) °C								
280.6 280.8 0	281 235								
um um r	nm HV		Reference:	237 HV 10					
n d, d,	d., Hardness	Mean value	Distance in						
μm μm r	nm HV	HV	mm	Remark					
1 317,6 314,5 0,	3160 186	4 4		1					
2 316,3 316,1 0,	3162 185	101							
3 318,8 317,0 0,	3179 184	181		BM 1					
4 321,7 323,0 0, 5 328,8 328,4 0	3223 170	4		•					
1 320.3 320.4 0.	3206 172								
2 315 3 314 2 0	3148 187	1 1							
3 311.6 310.3 0.	3109 192	188							
4 313.0 308.0 0.1	3105 192			HAZ1					
5 316.5 313.2 0.1	3149 187	1 1							
1 292,0 291,8 0,.	2919 218								
2 304,1 303,5 0,	3038 201	1 1							
3 310,1 308,4 0,	3093 194	202		WM					
4 306,4 307,0 0,3	3067 197	1 1							
5 302,0 303,7 0,3	3028 202] [
1 304,5 304,3 0,	3044 200								
2 301,2 303,5 0,	3023 203								
3 312,2 312,2 0,3	3122 190	193		HAZ 2					
4 315,5 316,3 0,	3159 186	1 1		CHO PROPERTY.					
5 315,3 315,3 0,3	3153 187								
1 331,3 331,9 0,3	3316 169	4 1		4					
2 320,1 325,5 U,	3238 1/5	176							
<u>3 322,0 323,0 0,</u> <u>4 321,0 324,0 0,</u>	3232 170	170		BIVI 2					
5 320.7 319.0 0	3199 181	1 1							
06.11.22 Scheck									
3 322,0 323,0 4 321,9 324,0 5 320,7 319,0 06.11.22 Scheck	5 0, 0 0, 0 0,	0 0,3232 178 0 0,3230 178 0 0,3199 181	0,3232 178 0 0,3230 178 0 0,3199 181	0,3230 178 0 0,3199 181					

Figure 3.4: Hardness measurements of L290 NE (1)

\mathbb{N}		ART	MF	Test rep PAS-PPB 523 Hardness	0 0rt 310-08/1 5 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	ber	9039784000	(
Sample desc	ription	39.1; Cente	er	122			
Sample description39.1; CenterAdministratorSilcherTest instrumentZwick 7 323							
			2 2				
Test instrum	Zwick Z 323	(neu)					
Serial numb	er	H2932-002-	50430				
Test conditions							
⊡ 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 temp	peratur, if out	side (23+/-	5) °C			
Control	280.6	280.8	0.281	235		1234	Press and a second second
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Bernarde
no.	μm	μm	mm	HV	HV	mm	Kemark
]	
1	324,8	326,5	0,3257	175		[]	
2	325,9	326,7	0,3263	1/4	474		
3	326,9	320,3	0,3266	174	1/4		BM 1
4	324,4	320.6	0,3239	173	1 1		
5	323,7	323,0	0,32/0	176			
2	321,1	317.6	0,3243	182	1 1		
3	320.3	319.4	0.3199	181	179		
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	1 1		
3	318,8	319,9	0,3193	182	181		BM
4	323,4	321,5	0,3224	178] [
5	325,0	322,3	0,3237	177			
1	323,8	326,3	0,3251	176	1 1		
2	330,0	330,0	0,3300	170			
3	321,9	321,5	0,3217	179	175		
4	324,2	323,4	0,3238	1//	4	-	
5	325,5	325,5	0,3255	1/5			
1	340,6	339,6	0,3401	160	4		
2	333.0	3246	0,3413	167	166		
3	329.4	329.4	0,3330	171	100		BM 2
4	327.9	330.6	0.3293	171	1 1		
5	521,0	000,0	0,0200				
Date: Tester:	06.11.22 Scheck						

Figure 3.5: Hardness measurements of L290 NE (2)

\mathbb{N}	STUTTGA		М	Test rej PAS-PPB 523 Hardnes	00rt 10-08/1 5 test	Re Metallo Elektrone	e ferat graphie und nmikroskopie
Order numb	er	9039784000	1				
Sample desc	ription	39.1; Root	i.		100		
Administrate	or	Silcher					
Administrator		Tuick 7 222	(nou)				
restinstrum	ent	ZWICK Z 323	(neu)				
Serial number	er	H2932-002-	50430				
Test conditio	ns						
HV ·	10	DIN EN ISO	6507-1:201	8-07			A CONTRACTOR OF
- HBW		DIN EN ISO	6506-1:201	5-02			
			6509 1.201	6 12			
I HKC	and the second		0000-1.201	0-12			
	Test temp	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,	d ₂	d _m	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	23438022355
1	323.8	320.8	0.3268	174			
2	336.3	329,0	0,3200	163			
3	335.2	335.8	0.3355	165	165		
4	334.6	333.3	0.3340	166			DIVI
5	341.6	341.0	0.3413	159			
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		
4	329,4	330,6	0,3300	170			
5	324,6	321,5	0,3231	178			
1	322,6	323,6	0,3231	178			
2	324,4	325,2	0,3248	176	1 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	332,7	0,3344	166			
2	329,6	336,5	0,3330	167			
3	335,0	332,7	0,3339	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			
3	338,7	338,9	0,3388	162	162		BM 2
4	337,9	339,0	0,3384	162			
5	329,0	333,5	0,3315	109			
Date:	06.11.22 Scheck	4					

Figure 3.6: Hardness measurements of L290 NE (3)

\mathbb{N}			M	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 5 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	ber	9039784000					
Sample desc	39.2; Outer	layer		100			
Administrat	or	Silcher					
Test instrum	nent	Zwick Z 323	(neu)				
Serial numb	er	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			
	Test temp	peratur, if out	side (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference	227 111/ 40
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	Nemark
্য	315.5	316.3	0 3150	186			
2	314.0	315.1	0,3146	180		-	- 11
3	314.0	315.1	0.3146	187	186		
4	315,7	317,4	0,3165	185		1	
5	319,2	318,4	0,3188	182		-	
1	306,8	309,7	0,3082	195			
2	305,1	305,7	0,3054	199	1.000	-	
3	311,1	312,4	0,3118	191	194		HAZ 1
4	312,2	311,8	0,3120	191			
5	310,9	310,5	0,3107	192			
1	299,9	301,4	0,3007	205		7	4
2	305,5	303,9	0,3047	200	100		
3	305.3	307.4	0,3078	198	155		
	309.5	306.2	0.3078	196			1
1	316.3	317.6	0.3170	185			
2	316,3	315,1	0,3157	186			1
3	313,6	314,0	0,3138	188	188	2	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	328,8	0,3292	171	475		
3	326,5	324,4	0,3255	1/5	1/5		BM 2
4	315.9	315.7	0,3238	186			1
5	5,5,5	010,7	0,0100	100			
Date:	06.11.22 Scheck						
Date: Tester:	06.11.22 Scheck	•		•			

Figure 3.7: Hardness measurements of L290 NE (4)

\mathbb{N}		ART	MP	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	ber	9039784000					
Sample description 39.2; Cent			r				
Administrat	or	Silcher					
Test instrum	ent	7wick 7 323	(neu)				
Forial numb		110000 000					
serial numb	er	H2932-002-	50430				
lest conditio	ons						
J HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC			6508 1.201	6 1 2			
	Test temp	eratur if out	side (23+4	5) °C			
Control	280.6	280.8	0.281	235		284	la constante
plate	um.	μm	mm	HV		Reference:	237 HV 10
indentation	d,	d,	d_	Hardness	Mean value	Distance in	(Bioline Mat)
10.	μm	μm	mm	HV	HV	mm	Kemark
1	321,5	325,0	0,3233	177			
2	321,7	324,0	0,3229	1/8	176		
3	327,3	324,2	0,3258	175	170		BM 1
4	325.9	327.1	0,3265	174			
1	318.8	321.7	0.3203	181			
2	319.9	319.9	0.3199	181	1 1		
3	321.3	320.9	0.3211	180	179		
4	323,0	319,4	0,3212	180	101040		
5	324,6	326,9	0,3258	175	1 1		
1	316,5	315,1	0,3158	186			
2	318,4	315,3	0,3169	185			
3	317,2	316,1	0,3166	185	183		WM
4	322,3	321,5	0,3219	179	1 1		
5	322,8	320,1	0,3214	180			
1	320,7	320,7	0,3207	180			
2	320,9	319,0	0,3200	181	100		
3	310.4	323,0	0,3224	1/8	180		HAZ 2
4	320.3	310.0	0,3190	181			
1	341.0	341.2	0.3411	159			
2	330.2	332.9	0.3316	169	1	-	1
3	326.1	324.8	0.3255	175	172		
4	321.7	322.8	0,3222	179			
5	322,5	325,5	0,3240	177			
Date:	06.11.22						
Tester:	Scheck						

Figure 3.8: Hardness measurements of L290 NE (5)

			MF	Test report MPAS-PPB 52310-08/1 Hardness test			e ferat graphie und enmikroskopie
Order numb	er	9039784000	6				
Sample desc	ription	39.2; Root					
Administrat	or	Silcher					
T-the		Zuick 7 222	(0011)				
lest instrum	ent	ZWICK Z 323	(neu)				
Serial number	er	H2932-002-	50430				
Test conditio	ins						No and A
HV	10	DIN EN ISO	6507-1:201	8-07			
HBW	7-700	DIN EN ISO	6506-1:201	5-02			
		DIN EN ISO	6508-1.201	6-12			
	Test tem	eratur if ou	teide (02+)	5)*C			
Contrat	280.6	200.0	0.204	225		111960	December 2010
Control	200,0	280,8	0,201	235		Reference:	237 HV 10
place t	- pm	- pin	- min d	nv l	Manual States	Distance in	
Indentation no.	um	um	mm	Hardness	HV HV	Distance in	Remark
	Part	part					
1	334,2	335.0	0,3346	166			
2	336,9	338,9	0,3379	162	163		1
3	331,5	334,4	0,3329	167			BM 1
4	340,6	341,0	0,3408	160			
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	0,3275	173			
5	326,1	323,4	0,3247	176			
1	328,0	326,5	0,3272	1/3			
2	327,8	327,9	0,3278	173	474		10/64
3	329,8	326,1	0,3279	172	174		VVIVI
4	325,7	324,4	0,3250	176			
1	323,3	321.7	0,3245	178			
2	323.6	323.4	0.3235	177			1
3	325.5	327.1	0.3263	174	176		HA7 2
4	327.1	329.0	0.3281	172			
5	324,0	324,6	0,3243	176			1
1	339,6	338,5	0,3391	161			
2	337,7	336,7	0,3372	163			
3	331,9	330,9	0,3314	169	166		BM 2
4	333,3	334,2	0,3338	166			
5	330,4	331,3	0,3309	169			
Date: Tester:	06.11.22 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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.15	0.14	0.57	0.017	0.02			
	Ni	V	Ti	Nb				

Table 3.6: Fracture toughness of 5L Grade A

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

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

Samples were taken from the base material.



Figure 3.10: Crack growth 5L Grade A

3.3 St35

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

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

The relevant material-specific data is as follows:

 Table 3.7: Characteristics of St35

Production year	1930		
Production standard	DIN 1629		
Specific minimum characteristics	R _e [MPa]	235	
	R _m [MPa]	350	
	K _v [J]	No requirements	
Material characteristics	R _e [MPa]	294	
	R _m [MPa]	458	
	K _v ² [J]	10	

Table 3.8: Chemical composition of St35

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
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
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				
Production standard	GOST 5520-79				
Specific minimum characteristics	R _e [MPa]	225			
	R _m [MPa]	370			
	K _v ⁴ [J]	39			
Material characteristics	R _e [MPa]	316			
	R _m [MPa]	458			
	K _v [J]	Not measured			

Table 3.14: Chemical composition of 15k (St35)

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

\sim			MF	Test report MPAS-PPB 52310-08/1 Hardness test		Referat Metallographie und Elektronenmikroskopie	
Order numb	ber	9039784000	e				
Sample description 23A5S-1		23A5S-1 O)uter layer				A CANADA SA
Administrat	or	Silcher	Silcher				
Test instrument		Zwick 7 323 (neu)				CONCEPTION OF	
rest instrument		Lionaa ana 50400					
Serial number		H2932-002-	50430				
Test condition	ons						
U HV	10	DIN EN ISO	6507-1:201	8-07		Ŧ	
HBW		DIN EN ISO	6506-1:201	5-02			
			6509 1:201	6 10			
LI HKC		DIN EN ISO	0508-1:201	0-12			
	Test temp	peratur, if out	side (23+/-	5) °C			
Control	280,6	280,8	0,281	235	Reference: 237 HV 10		
plate	μm	μm	mm	HV		the mathematical astronomy or a	
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	
	35/ 3	350 1	0 3567	146			
2	360.5	361.2	0,3507	140			BM 1
2	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			1
2	358.0	354.7	0,3564	146	147		HAZ 1
3	353,1	354,3	0,3537	148			
4	354,3	356,6	0,3555	147			
5	354,1	352,0	0,3531	149			
1	343,9	343,5	0,3437	157			
2	340,8	338,6	0,3397	161	155		WM
3	346,4	348,3	0,3474	154			
4	356,0	352,4	0,3542	148			
5	345,6	341,9	0,3437	157			
1	355,3	362,6	0,3590	144			
2	344,5	349,3	0,3469	154			
3	347,5	352,3	0,3499	151	149		HAZ 2
4	351,8	352,0	0,3519	146			4
5	354 7	356,3	0,3550	140			<u> </u>
2	35/ 3	357.4	0,3550	147	142		BM 2
2	363.4	364.9	0.3642	140			
4	363.7	367.6	0.3656	139		-	
5	365.3	370,5	0,3679	137			1
Date:	06.11.22					24	
Tester:	Scheck						

Figure 3.15: Hardness measurements of 15k (St35) (1)
\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000							
Sample desc	ription	23A5S-2 O	iter layer			6			
Administrate	or	Silcher							
Tort instrum	ont	Juiek 7 222	(2011)						
reschistrum	ent	ZWICK Z 323	(neu)						
Serial numbe	er	H2932-002-	50430	10-00					
Test conditio	ns								
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07		•			
HBW		DIN EN ISO	6506-1:201	5-02					
			CE00 1.001	0.40					
		DIN EN ISO	0508-1:201	0-12					
	Test temp	peratur, if out	side (23+/-	5) °C					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10		
plate	μm	μm	mm	HV		the management as many or a	-		
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	2010/06/07/06/06		
1	347.7	355.8	0.3517	150					
2	352,3	353,1	0,3527	149	148		1		
3	351,6	354,3	0,3530	149			BM 1		
4	356,4	359,5	0,3579	145					
5	350,6	353,9	0,3522	149	-				
1	362,2	363,9	0,3630	141			HAZ 1		
2	353,9	355,4	0,3546	147					
3	355,1	357,2	0,3562	146	146				
4	354,1	353,3	0,3537	148					
5	352.6	304,9	0,3543	140					
2	352,0	346.0	0,3308	152					
2	352.0	351.6	0,3490	150	151		WM		
4	354.7	353.3	0,3540	148	101				
5	350.2	347.0	0.3486	153			1		
1	367.2	369,3	0,3682	137					
2	352,4	350,4	0,3514	150			1		
3	353,9	352,4	0,3532	149	147		HAZ 2		
4	353,5	350,8	0,3521	150]		
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	353,1	0,3520	150			4		
5	351,8	356,6	0,3542	148					
n an		1	-						
Date:	06.11.22								
Tester:	Scheck								



\mathbb{N}			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie			
Order numb	ber	9039784000	È.						
Sample desc	ription	23A5S-2	Root						
Administrat	or	Silcher							
Test laster		7	(maril)						
lest instrum	ient	ZWICK Z 323	(neu)						
Serial numb	er	H2932-002-	50430						
Test conditio	ons								
U HV	10	DIN EN ISO	6507-1:201	8-07					
HBW		DIN EN ISO	6506-1.201	5-02					
			0000 1.201						
L HKC		DIN EN ISO	0508-1:201	0-12					
	Test temp	peratur, if out	side (23+/-	5) *C					
Control	280,6	280,8	0,281	235		Reference:	237 HV 10		
plate	μm	μm	mm	HV			201 111 10		
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark		
1	359,5	365,1	0,3623	141	144				
2	357.6	369,9	0,3663	138					
4	361.4	364.7	0,3630	143					
5	340,0	348,1	0,3440	157					
1	374,7	363,2	0,3689	136					
2	353,7	351,0	0,3523	149					
3	352,9	351,4	0,3521	150	146		HAZ 1		
4	353,7	352,4	0,3531	149					
5	355,0	353,5	0,3547	147					
2	342.1	344.3	0.3432	157					
3	336.9	335.8	0.3364	164	159	-	WM		
4	337,9	338,7	0,3383	162			1		
5	348,3	347,9	0,3481	153					
1	356,0	355,5	0,3558	147					
2	353,7	352,0	0,3529	149	100				
3	353,9	353,5	0,3537	148	148		HAZ 2		
4	351,8	351,2	0,3515	145					
5	364 7	365.0	0,3571	140			-		
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			1		
5	358,7	363,2	0,3610	142					
Date: Tester:	06.11.22 Scheck								
.coch	Guileur								

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

\mathbb{N}	STUTTG		Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Order numb	er	9039784000	e				
Sample desc	ription	23C.1; Out	er layer				and the second second
Administrat	or	Silcher	A STATE OF THE STA			并不能的关系。	
Test instrum	ent	Zwick Z 323	(neu)				
Serial number	er	H2932-002-	50430				
Test conditio	ins						
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	eratur if out	side (23+4	5) *C			
Control	280.6	220.9	0.291	225		35923	Deservation of
plate	200,0	200,0	0,201 mm	HV		Reference:	237 HV 10
Indontation	d.	d.	d	11-12-1	Maan yalua	Distance in	
no.	μm	μm	mm	Hardness	HV	mm	Remark
		1					
1	355,8	362,8	0,3593	144			
2	355,3	361,4	0,3584	144	145		1
3	348,7	355,6	0,3521	150			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	150		HAZ 1
3	341,2	345,0	0,3431	150	100		
4	341,0	345,4	0,3435	157		-	
5	342,9	328.0	0,3446	170			
2	325.0	328.8	0,3269	174			
3	325.9	330.0	0.3280	172	175		
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	350,8	0,3476	154			1
3	351,2	344,8	0,3480	153	153		HAZ 2
4	347,9	350,0	0,3489	152			
5	344,6	347,0	0,3458	155			
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			
5	352,7	354,9	0,3538	148			
Date:	06.11.22 Scheck						
reater.	Juneux						



\mathbb{N}		NRT	MF	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numl	ber	9039784000	ĺ.					
Sample desc	ription	23C.1; Roo	t					
Administrat	or	Silabor						
		Silcher	38					
lest instrun	nent	Zwick Z 323	(neu)			• •		
Serial numb	er	H2932-002-	50430					
Test condition	ons			1. 1. A.	and the second second			
⊡ 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		5		
	Test temp	eratur. if out	side (23+4	5) °C				
Control	280.6	280.8	0.281	235		12842	lesero cero	
plate	um	um	mm	HV		Reference:	237 HV 10	
Indentation	d.	d,	d	Hardness	Mean value	Distance in		
no.	um	um	mm	HV	HV	mm	Remark	
		1						
া	344,8	349,8	0,3473	154				
2	343,3	346,0	0,3447	156	10 January]	
3	348,9	357,6	0,3533	149	149		BM 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	3/2.0	349,8	0,3512	150	154		HAZ 1	
3	341.0	343,1	0,3403	158	134			
	344.4	343.8	0,3441	157		-	1	
1	332.3	330.6	0.3315	169				
2	333,3	334,8	0,3341	166			1	
3	338,9	336,3	0,3376	163	166		WM	
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	457			
3	341,1	340,8	0,3410	160	157	,		
4	342.3	343.7	0.3430	158			1	
1	362.0	363.9	0.3629	141				
2	363.9	371.5	0,3677	137			1	
3	365,7	367,8	0,3668	138	140		BM 2	
4	363,4	365,7	0,3646	140]	
5	355,6	359,5	0,3575	145		u		
T	21-21-21-C							
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Order numb	er	9039784000		$b = \frac{1}{2} b$				
Sample desc	ription	23C.2; Out	er layer					
Administrat	or	Silcher						
T 11 1		Zuiek 7 222	(2011)					
lest instrum	ient	ZWICK Z 323	(neu)					
Serial numb	er	H2932-002-	50430					
Test conditio	ons							
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				
	-		-14- 100-11	5110				
	rest temp	eratur, if out	side (23+/-	3) 0		Ulbor	Theory of the second	
plate	280,6	280,8	0,281	235		Reference:	237 HV 10	
Indontation	d.	d.	d	Unredmaner	Mean value	Distance in		
no.	um	um	mm	Hardness	HV	mm	Remark	
		-						
1	353,7	358,0	0,3559	146				
2	346,4	349,1	0,3478	153	148			
3	354,5	359,3	0,3569	146			BM 1	
4	352,9	359,1	0,3560	146				
5	354,1	350,4	0,3552	147				
2	331.0	<u>88=,</u> ‡	0,3328	170				
2	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	321,5	0,3189	182				
2	324,2	318,6	0,3214	180				
3	320,3	315,9	0,3181	183	182		WM	
4	322,1	320,5	0,3213	180				
5	320,7	315,7	0,3182	183				
2	347,0	342,9	0,3450	155				
2	339.2	339.6	0,3441	161	159		ΗΔ7 2	
4	343.9	336.7	0.3403	160	100			
5	340.8	340.4	0,3406	160				
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	361,6	0,3585	144				
5	353,9	358,0	0,3560	146				
Data:	06 11 00	_	-					
Date:	06.11.22							
Tester:	Scheck							



\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Order numb	ber	9039784000)					
Sample desc	ription	23C.2; Roo	t					
Administrat	or	Silcher						
Test lasteur		7	(
lest instrum	ient	ZWICK Z 323	(neu)					
Serial numb	er	H2932-002-	50430					
Test conditio	ons							
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 tops	aratur if aut	rida /22+/	51.10				
	Test temp	eratur, ir out	Side (23+/-	5) 0				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
protection			d	riv 	Manual station	Distance in	-	
Indentation	a ₁	α ₂	a _m	Hardness	HV HV	Distance in	Remark	
110.	Paul	pin						
1	342,5	346.2	0.3444	156			-	
2	343,9	350,4	0,3472	154	152	Î.	1	
3	350,6	350,8	0,3507	151			BM 1	
4	354,1	353,7	0,3539	148				
5	349,6	352,7	0,3511	150				
1	330,9	329,8	0,3303	170		н. — — — — — — — — — — — — — — — — — — —		
2	344,6	343,1	0,3438	157	450		HAZ 1	
3	354,1	351,4	0,3528	149	156			
4	354,7	301,0	0,3533	149				
5	335.8	333 1	0,3474	166				
2	335.0	329.2	0.3321	168				
3	335.2	330.6	0.3329	167	168	-	\//M	
4	329,8	326,5	0,3282	172		1		
5	333,1	329,6	0,3314	169			1.	
1	347,5	342,3	0,3449	156				
2	344,3	340,2	0,3423	158				
3	348,7	344,8	0,3467	154	155	-	HAZ 2	
4	347,3	343,1	0,3452	156				
5	350,2	346,0	0,3481	153				
1	348,1	303,3	0,3507	151			•	
2	348.9	351.4	0.3502	151	152			
4	346.2	352.0	0.3491	152	102			
5	340,8	351,0	0,3459	155				
Date: Tester:	06.11.22 Scheck							
Tester:	Scheck							

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

3.5 X42

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

The relevant material-specific data is as follows:

Table 3.16: Characteristics of X42

Production year	1961				
Production standard	DIN 2470 / API Special Regulations (API 5 LX)				
Specific minimum characteristics	R _e [MPa]	289 (29.5 kg/mm ²)			
	R _m [MPa]	414 (42.2 kg/mm²)			
	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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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}			MF	Test rep PAS-PPB 523 Hardness	00071 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order num	ber	9039784000	r.				
Sample des	cription	3LN-1 Oute	er layer				
Administrat	tor	Silcher					
Test instrum	nent	Zwick Z 323	(neu)				
Serial numb	er	H2932-002-	50430				
Test conditi	ons						
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 temp	eratur, if out	side (23+/-	5) °C			
Control	280,6	280,8	0,281	235		Reference	227 41/ 40
plate	μm	μm	mm	HV		neierence.	237 HV 10
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	312,4	319,0	0,3157	186			
2	312,0	316.0	0,3153	187			•
4	308.8	316,1	0.3125	190		1	
5	309,3	314,7	0,3120	191			1
6	308,6	313,2	0,3109	192	1]
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	309,9	312,0	0,3108	192	·		•
12	310,1	312.0	0.3110	192			
13	311,3	313,0	0,3122	190			1
14	311,5	311,1	0,3113	191			
15	305,7	303,3	0,3045	200			
16	305,5	305,7	0,3056	199			
17	311.3	312,0	0,3120	191			
19	310.1	312.6	0.3113	191			1
20	311,1	314,0	0,3126	190			1
21	311,6	314,0	0,3128	190			
22	309,9	312,0	0,3109	192			4
23	306,8	309,9	0,3083	195			•
							-
Date: Tester:	06.11.22 Scheck						
uniter de VEUS - A							

Figure 3.23: Hardness measurements of X42 (1)

\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Order num	ber	9039784000)					
Sample des	ription	3 LN-1 Ro	ot					
Administrat	or	Silcher						
Test instrun	nent	Zwick Z 323	(neu)					
Serial numb	er	H2932_002_	50430					
Test south		112932-002-	50450					
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				
	Test temp	eratur, if out	tside (23+/-	5) *C				
Control	280,6	280,8	0,281	235	B -1			
plate	μm	μm	mm	HV		Neierence.	237 HV 10	
Indentation no.	d₁ µm	dz µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark	
1	311,5	318,2	0,3149	187		-		
2	317.4	320,1	0,3105	165				
4	316.7	323,4	0,3201	181				
5	315,7	318,8	0,3173	184				
6	319,0	323,2	0,3211	180				
7	319,9	324,4	0,3221	179				
8	320,5	325,2	0,3229	178				
9	318.6	323,0	0,3224	1/8				
11	318.0	322.3	0,3214	181				
12	318,4	321,7	0,3201	181				
13	317,0	314,0	0,3155	186				
14	311,6	311,1	0,3113	191				
15	320,5	322,3	0,3214	180				
10	317.6	320,9	0,3200	181				
18	317.8	321.3	0,3195	182				
19	318,8	321,7	0,3203	181				
20	320,3	322,5	0,3214	180				
21	319,6	322,1	0,3209	180				
22	313,2	517,0	0,3155	100				
							1	
Dete								
Date:	06.11.22							
Tester:	Scheck							

Figure 3.24: Hardness measurements of X42 (2)

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 5 test	Referat Metallographie und Elektronenmikroskopie	
Order num	ber	9039784000	i -				
Sample des	ription	3 LN-2 Out	er layer			5. 19 A.	
Administrat	or	Silcher					
Test instrun	nent	Zwick 7 323	(neu)				
Social numb	or	L10022 002	(IICU) 50420				
Serial numb		H2932-002-3	50430				
Test condition	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			
	Test temp	eratur if out	tside (22+1	5) °C			
Control	220 6	220.2	0.291	225		500	Transfer Income
plate	200,0 um	200,0 um	0,201 mm	HV		Reference:	237 HV 10
Indentation	d.	d,	d	Hardness	Mean value	Distance in	
no.	μm	μm	mm	HV	HV	mm	Remark
1	308,4	314,3	0,3113	191			
2	309,3	315,7	0,3125	190			
3	305,3	313,2	0,3093	194			
4	310.9	315.7	0,3089	194		-	
6	307.8	310.3	0,3091	194			
7	312.8	315,1	0.3139	188			
8	310,3	311,3	0,3108	192			
9	310,5	312,2	0,3113	191			
10	310,7	311,5	0,3111	192			
11	306,8	311,3	0,3091	194			
12	307,6	310,3	0,3090	194			
13	301,8	301,0	0,3014	204			
14	307,4	304,5	0,3059	198			
15	310.1	313,8	0,3119	191		-	
10	308.6	313.6	0.3111	192			
18	310.7	312.8	0.3118	191			
19	312,6	315,1	0,3138	188			
20	312,6	315,3	0,3139	188			
21	312,4	315,7	0,3140	188			
22	310,7	315,3	0,3130	189			
23	311,6	316,5	0,3140	188			
24	313,6	318,4	0,3160	186			
		_	_			-	
Date: Tester:	06.11.22 Scheck						
5. S.							

Figure 3.25: Hardness measurements of X42 (3)

Order number 9039784000 Sample description 3 LN-2 Root Administrator Silcher Test instrument Zwick Z 323 (neu Serial number H2932-002-50430 Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number Image: Serial number<	-1:2018-(-1:2015-(-1:2016-' (23+/-5) 281 m 1 m 102 105 106 106 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Sample description 3 LN-2 Root Administrator Silcher Test instrument Zwick Z 323 (neu Serial number H2932-002-50430 Test conditions Image: Conditions Image: HV 10 DIN EN ISO 6507 HBW DIN EN ISO 6508 HRC DIN EN ISO 6508 Image: Test temperatur, if outside Control 280,6 280,8 0, plate µm µm n Indentation d1 d2 0 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 3 307,8 313,4 0,3 3 307,8 312,6 0,3 3 307,8 312,6 0,3 1 319,2 322,3 0,3 3	-1:2018-(-1:2015-(-1:2016-' (23+/-5) 281 m 1 102 105 106 116 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Administrator Silcher Test instrument Zwick Z 323 (neu Serial number H2932-002-50430 Test conditions Image: Conditions Image: HV 10 DIN EN ISO 6507 HBW DIN EN ISO 6508 HRC DIN EN ISO 6508 Test temperatur, if outside Control Z80,6 280,8 0, plate µm µm n Indentation d₁ d₂ 0 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 1 306,4 314,2 0,3 3 307,8 313,4 0,3 1 306,4 312,6 0,3 3 307,8 313,4 0,3 3 307,8 313,4 0,3 1 318,2 320,3 0,3 1 319,9 322,3 0,3 1	-1:2018-(-1:2015-(-1:2016- (23+/-5) 281 m 102 105 106 106 116 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Test instrument Zwick Z 323 (neu Serial number H2932-002-50430 Test conditions Image: Conditions ✓ HV 10 DIN EN ISO 6507 → HBW DIN EN ISO 6506 → HRC DIN EN ISO 6508 → Test temperatur, if outside Control 280,6 280,8 0, plate µm µm n Indentation d1 d2 0 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 4 308,4 312,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 10 318,0 320,7 0,3 11 <t< th=""><th>-1:2018-(-1:2015-(-1:2016-' (23+/-5)) 281 m 1 102 105 106 116 116</th><th>07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185</th><th>Mean value HV</th><th>Reference: Distance in mm</th><th>237 HV 10 Remark</th></t<>	-1:2018-(-1:2015-(-1:2016-' (23+/-5)) 281 m 1 102 105 106 116 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Serial number H2932-002-50430 Test conditions IN EN ISO 6507 HV 10 DIN EN ISO 6506 HRC DIN EN ISO 6508 Test temperatur, if outside Control Control 280,6 280,8 plate µm µm Indentation d₁ d₂ 1 306,4 314,0 0.3 2 306,8 314,2 0.3 3 307,8 313,4 0.3 1 306,4 314,2 0.3 3 307,8 313,4 0.3 2 306,8 314,2 0.3 3 307,8 313,4 0.3 3 307,8 313,4 0.3 4 308,4 312,8 0.3 5 310,5 312,6 0.3 6 314,7 318,8 0.3 3 307,8 312,6 0.3 10 318,0 320,9 0.3 </td <td>-1:2018-(-1:2015-((23+/-5) 281 m 102 105 106 106 116</td> <td>07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185</td> <td>Mean value HV</td> <td>Reference: Distance in mm</td> <td>237 HV 10 Remark</td>	-1:2018-(-1:2015-((23+/-5) 281 m 102 105 106 106 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Image: Serial number H2332-002-30430 Test conditions Image: Serial number Image: HW 10 DIN EN ISO 6507 Image: HBW DIN EN ISO 6508 Image: HRC DIN EN ISO 6508 Image: Test temperatur, if outside DIN EN ISO 6508 Control 280,6 280,8 0, plate µm µm n Indentation d₁ d₂ 0, 1 306,4 314,0 0,5 2 306,8 314,2 0,5 3 307,8 313,4 0,5 3 307,8 313,4 0,5 3 307,8 314,2 0,5 3 307,8 313,4 0,5 3 307,8 314,2 0,5 3 307,8 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 1 319,9 322,3 0,3 10 318,0 320,7 0,3 11 319,2 <t< td=""><td>-1:2018-(-1:2015-(-1:2016-' (23+/-5) 281 m lm lm lm lm l102 105 106 106 116</td><td>07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185</td><td>Mean value HV</td><td>Reference: Distance in mm</td><td>237 HV 10 Remark</td></t<>	-1:2018-(-1:2015-(-1:2016-' (23+/-5) 281 m lm lm lm lm l102 105 106 106 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Itest conditions HV 10 DIN EN ISO 6507 HBW DIN EN ISO 6508 HRC DIN EN ISO 6508 Test temperatur, if outside Control 280,6 280,8 0, plate µm µm n Indentation d1 d2 0 1 306,4 314,0 0,3 2 306,8 314,2 0,3 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 4 308,4 312,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 9 318,2 320,3 0,3 10 318,0 320,7 0,3 11 319,2 320,3 0,3 11 319,8 318,2 0,3	-1:2018-(-1:2015-((23+/-5)) 281 m 1 m 102 105 106 116 116	07 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
HV 10 DIN EN ISO 6507 HBW DIN EN ISO 6508 HRC DIN EN ISO 6508 Test temperatur, if outside DIN EN ISO 6508 Control 280,6 280,8 0, plate µm µm n Indentation d₁ d₂ 0 1 306,4 314,0 0,5 2 306,8 314,2 0,5 3 307,8 313,4 0,5 4 308,4 312,8 0,5 5 310,5 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 9 318,2 320,3 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 11 319,2 320,3 0,3 11 319,2 320,3 0,3 12 318,6 320,7 0,3 <td< td=""><td>-1:2018-(-1:2015-(-1:2016-' (23+/-5) 281 m lm lm lm lm lm lm l102 105 106 106 106 116</td><td>07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185</td><td>Mean value HV</td><td>Reference: Distance in mm</td><td>237 HV 10 Remark</td></td<>	-1:2018-(-1:2015-(-1:2016-' (23+/-5) 281 m lm lm lm lm lm lm l102 105 106 106 106 116	07 02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
HBW DIN EN ISO 6506 HRC DIN EN ISO 6508 Test temperatur, if outside Control plate 280,6 280,8 0, µm µm µm n Indentation no. µm µm µm n 1 306,4 314,0 0,3 0,3 2 306,8 314,2 0,3 0,3 1 306,4 314,0 0,3 0,3 2 306,8 314,2 0,3 0,3 3 307,8 313,4 0,5 310,5 312,6 0,3 4 308,4 312,8 0,3 0,3 0,3 0,3 5 310,5 312,6 0,3	-1:2015-(-1:2016-' (23+/-5) 281 m 102 102 105 106 116 167	02 12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
HRC DIN EN ISO 6508 Test temperatur, if outside Control plate 280,6 280,8 0, μm μm μm n Indentation no. d₁ d₂ 0, 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 4 308,4 312,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 9 318,2 320,3 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 11 319,2 320,3 0,3 11 319,8 318,2 0,3 11 319,8 318,2 0,3 11 319,8 318,2 0,3	-1:2016- (23+/-5) 281 m 1 m 102 105 106 106 106 116 167	12 *C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Test temperatur, if outside Control 280,6 280,8 0, plate μm μm n Indentation d₁ d₂ 0 no. μm μm n 1 306,4 314,0 0,5 2 306,8 314,2 0,5 3 307,8 313,4 0,5 3 307,8 313,4 0,5 3 307,8 313,4 0,5 3 307,8 313,4 0,5 5 310,5 312,6 0,5 6 314,7 318,8 0,5 7 318,2 320,3 0,5 10 318,0 320,9 0,5 11 319,2 320,3 0,5 11 319,2 320,3 0,5 11 319,2 323,0 0,5 11 319,2 323,0 0,5 113 321,9 323,0 <td< td=""><td>(23+/-5) 281 im im im 102 105 106 106 116 167</td><td>*C 235 HV Hardness HV 193 192 192 192 191 185</td><td>Mean value HV</td><td>Reference: Distance in mm</td><td>237 HV 10 Remark</td></td<>	(23+/-5) 281 im im im 102 105 106 106 116 167	*C 235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
Control plate 280,6 280,8 0, µm Indentation no. d1 d2 0 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 4 308,4 312,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 9 318,2 320,3 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 11 319,2 323,0 0,3 11 319,8 318,2 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 15 319,8 318,2 0,3 1	281 m 102 105 106 106 116 167	235 HV Hardness HV 193 192 192 192 191 185	Mean value HV	Reference: Distance in mm	237 HV 10 Remark
plate μm μm n Indentation no. d1 μm d2 μm μm n 1 306,4 314,0 0,5 2 306,8 314,2 0,5 3 307,8 313,4 0,5 4 308,4 312,8 0,5 5 310,5 312,6 0,5 6 314,7 318,8 0,5 7 318,2 320,3 0,5 8 319,9 322,3 0,5 9 318,2 320,3 0,5 10 318,0 320,9 0,5 11 319,2 320,3 0,5 11 319,2 320,3 0,5 11 319,2 320,3 0,5 12 318,6 320,7 0,5 13 321,9 313,8 0,5 14 315,9 313,8 0,5 15 319,8 318,2 0,5	102 105 106 106 116 116	HV Hardness HV 193 192 192 192 192 191 185	Mean value HV	Keference: Distance in mm	237 HV 10 Remark
Indentation no. d1 µm d2 µm n 1 306,4 314,0 0,3 2 306,8 314,2 0,3 3 307,8 313,4 0,3 4 308,4 312,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 8 319,9 322,3 0,3 9 318,2 320,3 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 12 318,6 320,7 0,3 13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19	102 105 106 106 116 116	Hardness HV 193 192 192 192 191 185	Mean value HV	Distance in mm	Remark
Image Image <t< td=""><td>102 105 106 106 116 116</td><td>193 192 192 192 192 191 185</td><td></td><td></td><td></td></t<>	102 105 106 106 116 116	193 192 192 192 192 191 185			
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	102 105 106 106 116 167	193 192 192 192 192 191 185			
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	105 106 106 106 116 167	192 192 192 191 185			
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	106 106 116 167	192 192 191 185			
4 308,4 312,8 0,3 5 310,5 312,6 0,3 6 314,7 318,8 0,3 7 318,2 320,3 0,3 8 319,9 322,3 0,3 9 318,2 320,4 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 11 319,2 320,3 0,3 11 319,2 320,3 0,3 12 318,6 320,7 0,3 13 321,9 323,0 0,3 13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3 19	106 116 167	192 191 185		-	
5 310,5 312,6 0,7 6 314,7 318,8 0,7 7 318,2 320,3 0,7 8 319,9 322,3 0,7 9 318,2 320,4 0,7 10 318,0 320,9 0,7 11 319,2 320,3 0,7 11 319,2 320,3 0,7 11 319,2 320,3 0,7 12 318,6 320,7 0,7 13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3 19 320,3 323,2 0,3	116	191			
0 314,7 310,8 0,3 7 318,2 320,3 0,5 8 319,9 322,3 0,5 9 318,2 322,4 0,5 10 318,0 320,9 0,5 11 319,2 320,3 0,5 11 319,2 320,3 0,5 11 319,2 320,3 0,5 12 318,6 320,7 0,5 13 321,9 323,0 0,5 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3 20 320,4 323,0 0,3	10/	0.0			-
7 310,2 320,3 0,3 8 319,9 322,3 0,3 9 318,2 322,4 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 12 318,6 320,7 0,3 13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	102	182			
9 318,2 322,4 0,3 10 318,0 320,9 0,3 11 319,2 320,3 0,3 12 318,6 320,7 0,3 13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	211	180	1 1		
10 318,0 320,9 0,7 11 319,2 320,3 0,7 12 318,6 320,7 0,7 13 321,9 323,0 0,7 14 315,9 313,8 0,7 15 319,8 318,2 0,7 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,5 19 320,3 323,2 0,5	203	181			
11 319,2 320,3 0,3 12 318,6 320,7 0,3 13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	194	182	1 1		1
12 318,6 320,7 0,5 13 321,9 323,0 0,5 14 315,9 313,8 0,5 15 319,8 318,2 0,5 16 317,4 322,8 0,5 17 320,3 323,8 0,5 18 319,4 323,0 0,5 19 320,3 323,2 0,5	198	181	1 1]
13 321,9 323,0 0,3 14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	196	181	1 1	-	
14 315,9 313,8 0,3 15 319,8 318,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	224	178	1 1		
15 319,8 316,2 0,3 16 317,4 322,8 0,3 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	149	187			
10 317,4 322,5 6, 17 320,3 323,8 0,3 18 319,4 323,0 0,3 19 320,3 323,2 0,3	201	102			-
18 319,4 323,0 0,3 19 320,3 323,2 0,3	220	179	1 1		1
19 320,3 323,2 0,3	212	180	1 1		1
00 0004 0014	217	179	1 1		1
20 320,1 321,1 0,3	206	180] []
21 317,8 323,2 0,3	205	181	[1
22 316,1 323,0 0,3	195	182			4
23 310,3 323,4 0,3	199	181		-	4
24 514,7 525,2 0,3	103	102			
				-	
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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.17	0.26	0.93	0.0025	0.0017			
	Ni	V	Ti	Nb				

Table 3.21: Fracture toughness of RR St43.7

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

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



Figure 3.27: Crack growth RRSt43.7

3.7 P355 NH/NL2

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

The relevant material-specific data is as follows:

Table 3.22: Characteristics of P355 NH/NL2

Production year	2019			
Production standard	DIN EN 10028-3 (10/17)			
Specific minimum characteristics	R _e [MPa]	355		
	R _m [MPa]	490		
	K _v ⁶ [J]	27		
Material characteristics	R _e [MPa]	389		
	R _m [MPa]	541		
	Kv ⁶ [J]	108		

Table 3.23: Chemical composition of P355 NH/NL2

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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
[%]	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			
	K _v [J]	145			

Table 3.29: Chemical composition of L360NB

Chamies Leanna esitien	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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
	K _v [J]	Ø 107

Table 3.32: Chemical composition of X46 / StE320.7

	С	Si	Mn	Р	S	Cu	Cr	Мо
composition [%]	0.23	0.23	0.94	0.015	0.037	0.18	0.04	0.01
	Ni	V	Ti	Nb		<u>.</u>	<u>.</u>	•
	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

Chemical composition [%]	С	Si	Mn	Р	S	Cu	Cr	Мо
	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}	STUTTGA		MP	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	0				
Sample desc	ription	18.1; Outer	layer				
Administrate	or	Silcher					
Tort instrum	ant	Zuick 7 222	(0011)				
Serial number	ent	LANCK 2 323	(neu) 50430				
Tect conditio		112002-002-0	50450				
			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 ou	tside (23+/	-5) *C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV			
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	292,5	300,8	0,2966	211			
2	293,9	301,6	0,2977	209			
3	294,9	301,6	0,2983	208			
4	292,0	298,9	0,2955	212			
5	291,2	297,0	0,2941	214		1.	
7	289,1	293,0	0,2920	217			
8	286.9	292.7	0.2898	221			
9	285,6	291,0	0,2883	223			
10	284,2	290,6	0,2874	225			
11	281,9	275,2	0,2785	239			
12	273,2	267,5	0,2704	254			
13	278,3	287,7	0,2830	232			
14	280,2	287,9	0,2840	230			
15	287,3	290,2	0,2887	222			
10	204,0	207,3	0,2659	227			
18	287.9	288.7	0.2883	223			
19	289.6	293.1	0,2913	219		1	
20	287,7	294,3	0,2910	219			
21	287,9	290,2	0,2890	222			
22	287,9	283,6	0,2857	227			
						-	
		ł – – –					
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}		ART	М	Test rep PAS-PPB 523 Hardness	00rt 810-08/1 5 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	1				
Sample desc	ription	18.1; Root	t				
Administrato	or	Silcher					
Test instrum	ent	Zwick 7 323	(neu)				
Serial numbe	er	H2932-002-	(neu) 50430				
Test conditio	ons	112002 002					
⊡ 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		References	227 444
plate	μm	μm	mm	HV		neierence.	237 HV 10
Indentation	d,	d₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	25/28/2020/058
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			1
5	294,9	305,1	0,3000	206			1
6	293,3	304,7	0,2990	207			1
7	295,8	303,0	0,2994	207			1
8	294,3	302,2	0,2983	208			1
9	293,3	300,3	0,2968	210			
10	292,5	296,8	0,2946	214			
11	285,8	291,6	0,2887	222			
12	289,4	293,7	0,2915	218			
13	291,8	298,9	0,2954	213			
14	283,9	291,6	0,2878	224			
15	288,3	294,5	0,2914	218			
16	294,9	298,7	0,2968	210			4
1/	293,9	299,7	0,2908	210			
10	293,9	296.8	0 2940	205			
20	291.4	298.5	0.2949	213			1
	201,4	200,0	0,2040	210			
							1
Data:	06 44 00	1					
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	00071 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	1				
Sample desc	ription	18.2; Outer	layer				
Administrate	or	Silcher					
Test instrum	ent	Zwick 7 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ons						Comparent and a second
I HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
HRC			6508-1:201	6-12			
	Test ten	peratur, if ou	tside (23+/	45) °C			
Control	280,6	280,8	0,281	235		Peter	00710140
plate	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	290,4	292,7	0,2915	218			
2	288,7	292,9	0,2908	219			
3	284,8	290,8	0,2878	224			
5	287.1	288.7	0.2879	224		-	
6	286,0	287,7	0,2869	225			
7	281,0	286,9	0,2839	230			
8	282,3	288,5	0,2854	228		[]]	
9	284,2	287,7	0,2859	227			
10	285,8	285,6	0,2857	227			
12	284,0	203,1	0,2635	231			
13	286.6	292.7	0.2897	220		-	
14	287.5	293.3	0.2904	220			
15	288,9	291,8	0,2904	220			
16	288,7	295,8	0,2922	217			
17	291,0	297,2	0,2941	214			
18	292,7	297,0	0,2948	213		-	
19	290,0	302,0	0,2990	200			
				ļ			
				-			
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}			M	Test rep PAS-PPB 523 Hardness	port 810-08/1 5 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000)				
Sample desc	ription	18.2; Root	t.				
Administrate	or	Silcher					
Test instrum	ent	Zwick 7 323	(neu)				
Serial numbe	er	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			
	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			257 114 10
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
			0.0070	010			
1	294,3	300,3	0,2973	210		_	
3	295,5	301,0	0,2972	208			
4	294,7	300,6	0,2976	209			
5	292,0	299,7	0,2959	212			
6	292,9	298,7	0,2958	212			
7	293,1	298,5	0,2958	212			
8	290,2	296,2	0,2932	216			
9	288,9	296,6	0,2928	210			
11	278.8	276.3	0,2320	241			
12	292,3	299,5	0,2959	212			
13	290,0	298,7	0,2943	214			
14	291,4	301,4	0,2964	211			
15	296,4	304,7	0,3006	205			
10	294,9	303,0	0,2990	207			
17	292,9	303.0	0,2975	209			
19	292,7	304,3	0,2985	208			
		1					
Date:	06.11.22						
Tester:	Scheck						

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

3.12 StE480.7 TM

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

The relevant material-specific data is as follows:

Table 3.37: Characteristics of StE480.7 TM

Production year	1997	
Production standard	DIN 17172	
Specific minimum characteristics	R _e [MPa]	480
	R _m [MPa]	600
	K _v [J]	48
Material characteristics	R _e [MPa]	508
	R _m [MPa]	616
	K _v [J]	253

Table 3.38: Chemical composition of StE480.7 TM

Chamieal	С	Si	Mn	Р	S	Cu	Cr	Мо
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	
Specific minimum characteristics	R _e [MPa]	360
	R _m [MPa]	460
	K _v ⁸ [J]	40
Material characteristics	R _e [MPa]	423
	R _m [MPa]	583
	K _v ⁸ [J]	156

Table 3.41: Chemical composition of L360 NB

Chemical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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 _{Jlc} [MPa \sqrt{m}]
L360 NB	Base material	20	128
L360 NB	Weld material of	20	132.4
	longitudinal weld		

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.

\mathbb{N}	STUTTGA	RT	MP	Test rep AS-PPB 523 Hardness	10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000					
Sample description		20HFLN-1;	Outer layer				
Administrato	or	Silcher					
		7. del: 7.222	(
Test instrum	ent	ZWICK Z 323	(neu)				
Serial numbe	er	H2932-002-	50430				
Test conditio	ins						
I HV	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1:201	5-02			
			6509 1.201	6.12			
	-	DIN EN ISU	0300-1.201	0-12			
	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	1.		
Indentation	a ₁	a ₂	a _m	Hardness	Mean value	Distance in	Remark
10.	293	301	0 2970	210			
2	294.5	301.4	0,2980	209			
3	270.7	280.6	0.2756	244			
4	262,2	263,6	0,2629	268			
5	262,8	265,1	0,2639	266			
6	259,9	261,9	0,2609	272			
7	258,2	259,0	0,2586	277			
8	253,8	256,1	0,2550	285			
9	255,7	256,1	0,2559	283			
10	255,7	255,7	0,2557	284			
11	204,5	259,4	0,2620	270			
12	270,0	275.6	0.2753	245			
13	285.4	289.6	0,275	224			
15	292.2	293.1	0.2927	216			
16	293,5	296,0	0,2947	213			
17	291,4	291,8	0,2916	218			
18	290,6	292,0	0,2913	219			
19	295,4	291,2	0,2933	216			
20	294,1	295,6	0,2948	213			
21	289,8	293,3	0,2915	218			
22	291,2	291,8	0,2915	210			
23	287.9	287.3	0.2876	224			
25	291.0	291.4	0,2912	219			
26	292,7	295,8	0,2942	214			
27	295,4	299,1	0,2972	210			
Date:	06.11.22						
Tester:	Scheck						

Figure 3.39: Hardness measurements of L360 NB (1)

\mathbb{N}	STUTTGA		MF	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000					
Sample desc	ription	20HFLN-1;	Root				
Administrato	or	Silcher					
Test instrum	ent	Zwick Z 323	(neu)		•		>
Serial numbe	er	H2932-002-	50430		Personal States		
Test conditio	ns						
⊡ HV	10	DIN EN ISO	6507-1:201	8-07			
- HBW		DIN EN ISO	6506-1:201	5-02			
L 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		Pafarana	00710140
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation no.	d₁ µm	dz µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
- 1	200.0	300.1	0 2951	213			
2	283.9	294.5	0,2951	213			
3	283,7	286,4	0,2851	228			
4	282,7	286,4	0,2846	229			
5	281,7	285,6	0,2836	230			
6	276,1	279,4	0,2777	240			
/	266,1	267,3	0,2667	261			
0 0	255,5	259,0	0,2573	285			
10	258.6	262.4	0,2005	273			
11	272,1	272,5	0,2723	250			
12	282,9	283,7	0,2833	231			
13	291,6	294,3	0,2930	216			
14	297,9	301,8	0,2998	206			
15	298,9	299,7	0,2993	207			
10	299,5	302,0	0,3007	205			
18	298.7	303.9	0,3013	204			
19	302,4	299,9	0,3012	204			
20	299,9	303,2	0,3016	204			
21	302,2	302,2	0,3022	203			
22	302,6	305,7	0,3042	200			
23	303,2	300,2	0,3047	200			
Date:	06.11.22	1					
Tester:	Scheck						

Figure 3.40: Hardness measurements of L360 NB (2)

\mathbb{N}	STUTTGA		Test report MPAS-PPB 52310-08/1 Hardness test		00071 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	Î				
Sample descr	ription	20HFLN-2,	Outer layer				
Administrate	or	Silcher					
Test instrum	ent	Zwick Z 323	(neu)				N. C.
Serial numbe	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			The second second
			0500-1.201	0.40			
HKC		DIN EN ISO	0508-1:201	0-12			
	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	Parts result in a section of		
Indentation no.	dı µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	294,3	295,2	0,2947	213			
2	295,2	295,4	0,2953	213			
3	288,9	291,6	0,2903	220			
4	284,4	287,7	0,2860	227			
5	200,7	200,3	0,2865	223			
7	209,4	205,0	0,2070	217			
8	288.9	293.7	0,2913	219			
9	289.1	293.3	0.2912	219			
10	288,7	288,9	0,2888	222			1
11	292,0	294,3	0,2932	216			1
12	289,8	294,3	0,2920	217			1
13	287,7	288,5	0,2881	223			
14	279,2	280,6	0,2799	237			4
15	264,9	272,7	0,2688	257			
16	260,9	205,3	0,2631	208			4
12	255,0	254,3	0.2537	200			
19	254.9	258.6	0.2568	281			1
20	255.7	256.1	0,2559	283			
21	261,7	261,9	0,2618	270			1
22	268,6	266,9	0,2678	259]
23	268,4	268,2	0,2683	258			
24	268,2	278,3	0,2733	248		-	
	energie and						
Date: Tester:	06.11.22 Scheck						

Figure 3.41: Hardness measurements of L360 NB (3)

\mathbb{N}	STUTTGA	RT	Test report MPAS-PPB 52310-08/1 Hardness test			Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	6				
Sample desc	ription	20HFLN-2;	Root				
Administrate	or	Silcher					
Test instrum	ent	Zwick Z 323	(neu)				
Serial number	er	H2932-002-	50430				
Test conditio	ons						
I HV	10	DIN EN ISO	6507-1:201	8-07		and a start of	
HBW		DIN EN ISO	6506-1:201	5-02			
HRC		DIN EN ISO	6508-1:201	6-12			
	Test tem	peratur, if ou	itside (23+/	45) *C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	Total and the second second		20111010
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark
1	296,8	299,1	0,2980	209			
2	302,8	303,9	0,3034	202		-	
3	304,7	306,8	0,3057	198			
	304.5	305.3	0,3049	199			
6	301,2	303,2	0,3022	203			
7	302,8	303,0	0,3029	202			
8	300,3	302,4	0,3014	204			
9	299,7	302,6	0,3012	204			
10	302,4	304,3	0,3033	202			
11	201.4	300,1	0,3001	206		-	
12	291,4	294,3	0,2929	210			
14	275.0	272.3	0.2737	248			
15	261,3	264,6	0,2630	268			
16	254,7	257,2	0,2559	283			
17	254,7	256,8	0,2557	284			
18	265,9	267,8	0,2668	260			
19	2/3,8	2/9,2	0,2/65	243			
20	285.4	284,8	0,2825	232			
21	283.3	287.7	0.2855	228			
23	279,6	292,9	0,2862	226			
		-					
Date:	06.11.22						
Tester:	Scheck						

Figure 3.42: Hardness measurements of L360 NB (4)
3.14 14HGS

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

The relevant material-specific data is as follows:

Table 3.43: Characteristics 14HGS

Production year	1964	
Production standard	GOST 5058 -65	
Specific minimum characteristics	R _e [MPa]	343
	R _m [MPa]	491
	K _v /A [kgm/cm ²]	4
Material characteristics	R _e [MPa]	392 (40 kp/mm²)
	R _m [MPa]	510 (52 kp/mm²)
	K _v /A [kgm/cm ²] ⁹	5

Table 3.44: Chemical composition of 14HGS

Ohamiaal	С	Si	Mn	Р	S	Cu	Cr	Мо
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}			MP	Test rep AS-PPB 523 Hardness	oort 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000	1					
Sample desc	ription	21LN-1; Out	er layer			ANY MANY		
Administrate	or	Silcher	Constant of the					
Test instrum	ent	ZWICK Z 323	(neu)					
Serial numbe	er	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				
			6500 1:201	6.10				
	Test	DIN EN ISO	0500-1.201	0-12 EV:0				
	lest tem	peratur, if ou	tside (23+/-	5) 0				
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
plate	μm	μm	mm	HV	The contraction	Dia la		
Indentation	a ₁	0 ₂	a _m	Hardness	Mean value HV	Distance in	Remark	
indi	Part	pan						
1	330,6	327,1	0,3289	171				
2	329,2	331,3	0,3302	170				
3	331,9	334,2	0,3330	167	168		BM 1	
4	335,2	335,6	0,3354	165				
5	333,1	333,6	0,3333	167				
1	308,4	308,0	0,3082	195				
2	204.3	301,4	0,3018	204	209			
3	294,5	299,5	0,2908	210	200		HAZ 1	
	294.5	294.9	0,2947	213				
1	329.4	329.8	0.3296	171				
2	332.7	331.9	0,3323	168				
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				
2	304,3	303,0	0,3037	201	204			
3	297,6	299,5	0,2986	208	204		HAZ 2	
4	297,0	202.0	0,2900	200				
1	328.6	327.8	0.3282	172	-			
2	324.4	324.0	0,3242	176				
3	326,3	325,2	0,3258	175	173		BM 2	
4	327,7	328,6	0,3282	172	10.000			
5	331,1	328,4	0,3297	171				
		1						
Date: Tester:	06.11.22 Scheck							



\mathbb{N}			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	21LN-1; Cer	nter			AN BORN		
Administrato	or	Silabor						
		Siicher						
Test instrum	ent	Zwick Z 323	(neu)					
Serial numbe	er	H2932-002-	50430					
Test conditio	ins							
⊡ HV	10	DIN EN ISO	6507-1.201	8-07			Carl State Street	
T HBW		DIN EN ISO	6506-1.201	5-02				
			0000 1.201	0.40				
	Test tem	DIN EN ISO	0008-1:2010	5) °C				
	000.0		0.001	-, -			7	
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
piace	µmd	µm.	mm	FIV		Distance in		
Indentation	a ₁	02 1000	a _m	Hardness	HV HV	Distance in	Remark	
	- Paris	part					-	
1	326,1	330,0	0,3281	172				
2	332,3	331,5	0,3319	168				
3	333,8	330,6	0,3322	168	167		BM 1	
4	334,6	340,0	0,3373	163				
5	335,6	337,1	0,3364	164				
1	301,0	296,4	0,2987	208				
2	300,8	300,8	0,3008	205				
3	302,0	301,6	0,3018	204	199		HAZ 1	
4	308,2	305,7	0,3070	197				
5	321,7	319,0	0,3204	181		-	-	
1	340,2	332,1	0,3362	164				
2	331,5	330,0	0,3307	170	160			
3	222.5	330,0	0,3322	100	100		VVIVI	
4	330.6	326.3	0,3325	172				
1	303.5	298.7	0.3011	205			i:	
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	308,2	0,3090	194				
1	332,7	338,8	0,3357	165		2		
2	327,1	334,4	0,3308	169	and the second se			
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			i	
Date:	06.11.22							
Tester:	Scheck							

Figure 3.45: Hardness measurements of 14HGS (2)

\mathbb{N}		RT	MP	Test rep AS-PPB 523 Hardness	ort 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	ier	9039784000						
Sample desc	ription	211 N_1 - R	oot					
Administrate	or	2110-1, 1						
To at location		Silcher						
lest instrum	ient	Zwick Z 323	(neu)					
Serial number	er	H2932-002-	50430					
Test conditio	ons							
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		02282	Press and a	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	Nemdik	
	200.0	004.0	0.0000	170				
1	329,2	331,3	0,3302	170				
2	331.9	320,3	0,3202	174	170			
4	327.1	333.4	0.3302	170	170		BIVET	
5	331.1	333.5	0.3323	168				
1	315,7	314,9	0,3153	187				
2	295,4	296,2	0,2958	212				
3	299,9	300,1	0,3000	206	193		HAZ 1	
4	320,7	312,2	0,3164	185				
5	327,1	326,5	0,3268	174				
1	336,7	336,5	0,3366	164				
2	333,1	329,4	0,3313	169	407		10/64	
3	333,2	327,7	0,3305	170	167			
4	337.1	329,0	0,3320	165				
1	309.1	307.0	0,3080	195				
2	312.6	310.1	0.3113	191				
3	315,5	310,1	0,3128	190	190		HAZ 2	
4	310,3	308,6	0,3095	194]	
5	323,2	322,1	0,3227	178				
1	331,3	327,3	0,3293	171				
2	321,9	325,2	0,3236	177	475			
3	324,0	325,0	0,3245	176	1/5		BW 2	
4	324,3	320,0	0,3264	176				
	020,0	024,0	0,0200	170				
Date:	06.11.22							
Tester:	Scheck							



\mathbb{N}	STUTTGA	RT	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	ber	9039784000						
Sample desc	ription	21LN-2, Out	ter layer		1. Sta	Teles .		
Administrate	or	Silahor	200					
				The second			APPENDER OF	
Test instrum	ient	Zwick Z 323	(neu)		Section States			
Serial numb	er	H2932-002-	50430					
Test condition	ons							
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				
П	Test tem	peratur, if ou	tside (23+/-	-5) °C				
Control	280.6	280.8	0.281	235		2274	lassonana.	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d,	d,,,	Hardness	Mean value	Distance in		
no.	μm	μm	mm	HV	HV	mm	Kemark	
1	310,1	308,9	0,3095	194				
2	312,8	310,5	0,3117	191	2000 and			
3	310,7	308,4	0,3096	193	192		BM 1	
4	310,9	314,3	0,3126	190				
5	312,0	312,6	0,3123	190				
1	287,3	284,6	0,2859	227				
2	279,6	281,9	0,2807	235				
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	0,3101	180	196		14/14	
3	321,7	312,0	0,3173	104	100			
4	317.8	310.0	0,3070	182			-	
1	284.4	285.8	0.2851	228				
2	287.1	282.1	0 2846	229	1 1			
3	282.7	285.4	0.2841	230	225		HA7 2	
4	288,9	288,7	0,2888	222			1	
5	292,9	290,2	0,2915	218			1	
1	312,6	314,0	0,3133	189				
2	312,0	314,3	0,3131	189				
3	318,4	315,1	0,3167	185	186		BM 2	
4	315,7	315,3	0,3155	186			1	
5	317,6	319,2	0,3184	183	1			
T ASSESSMENT							-	
Date: Tester:	06.11.22 Scheck							

Figure 3.47: Hardness measurements of 14HGS (4)

\mathbb{N}				Test rep AS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	21LN-2, Cer	nter		15%	A street Star		
Administrate	or.	Silebor						
Test instrum	ent	Zwick Z 323	(neu)					
Serial numbe	≥r	H2932-002-	50430					
Test conditio	ins				1997 NO			
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 out	tside (23+/-	5) *C				
Control	280.6	280.8	0.281	235			lane on the second	
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	
1	323,9	329,6	0,3267	174				
2	325,9	327,7	0,3268	1/4	170			
3	322,1	327,7	0,3249	176	170		BM 1	
4	222.4	322,0	0,3200	176			-	
J	200.0	203.3	0,3242	218				
2	290,0	295,5	0,2910	210			-	
2	292,2	290,0	0,2941	214	212			
4	296.2	299.1	0.2976	209	212		HAZ 1	
5	299.5	299.3	0 2994	203		-	-	
1	330.2	330.9	0,2004	170				
2	330.2	326.9	0.3286	172			1	
- 3	330.3	327.9	0.3291	171	171		I WM	
4	336.0	323.4	0.3297	171	i ferrer i		1	
5	328,2	333,4	0,3308	170	1 1		1	
1	292,7	296,0	0,2943	214				
2	297,2	299,1	0,2982	209				
3	296,8	297,8	0,2973	210	210	=	HAZ 2	
4	297,9	297,8	0,2979	209				
5	298,1	301,2	0,2996	207				
1	329,4	331,7	0,3305	170				
2	326,3	330,6	0,3285	172				
3	326,7	329,4	0,3281	172	1/2		BM 2	
4	326,5	327,3	0,3269	1/4			-	
5	320,3	331,1	0,3287	172				
Date: Tester:	06.11.22 Scheck							



\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 test	ort Re 10-08/1 Metallog test Elektroner		
Order numb	er	9039784000	6					
Sample desc	ription	21LN-2; R	oot		A.S.	All Star	and the second sec	
Administrato	or	Silebor			651977		A State	
lest instrum	ent	Zwick Z 323	(neu)					
Serial numbe	er	H2932-002-	50430					
Test conditio	ins							
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		Deferre		
plate	μm	μm	mm	HV		nererence:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	Keindik	
				100				
1	312,0	316,7	0,3144	188				
2	310,1	312,8	0,3115	191	100		BM 1	
4	310.1	313.0	0,3116	191	100			
5	315.1	312.0	0.3135	189				
1	306.8	302,0	0,3044	200				
2	294,5	292,5	0,2935	215	1			
3	295,6	300,1	0,2979	209	203		HAZ 1	
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	100			
3	331,7	326,9	0,3293	171	169		V V I V I	
4	332,7	330,7	0,3317	169		-		
5 1	303.7	301.2	0,3330	203				
2	305.1	304.5	0,3024	200				
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	320,9	0,3211	180				
2	316,1	315,9	0,3160	186	100000-000			
3	312,8	316,9	0,3149	187	184		BM 2	
4	317,4	317,6	0,3175	184				
5	316,5	317,6	0,3171	184				
Date: Tester:	06.11.22 Scheck							

Figure 3.49: Hardness measurements of 14HGS (6)

\mathbb{N}	STUTTGA	SRT	MF	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample descr	iption	21 UN (2); C	Outer layer					
Administrato	r	Silcher						
T		7 7 000	2.0.0					
lest 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				
HBW		DIN EN ISO	6506-1:201	5-02				
HRC			6508 1.201	6.12				
	Test ten	nperatur, if o	utside (23+	45) *C				
Control	280.6	280.8	0.281	235		280	less accord	
plate	um	μm	mm	HV		Reference:	237 HV 10	
Indentation	d.	d,	d	Hardness	Mean value	Distance in		
no.	μm	μm	mm	HV	HV	mm	Remark	
)	· · · · · · · · · · · · · · · · · · ·	
1	323,2	324,7	0,3240	177				
2	326,8	326,8	0,3268	174			1	
3	331,4	328,6	0,3300	170	172		BM 1	
4	333,9	327,8	0,3309	169				
5	331,9	332,4	0,3321	168				
1	365,0	327,0	0,3460	155				
2	297,9	303,3	0,3006	205			HAZ 1	
3	292,1	298,2	0,2951	213	198			
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	315,3	0,3192	182	105		10/11/1	
3	311,0	306,9	0,3089	194	100			
4	315.9	313.3	0,3219	1/9		-		
1	304.1	301.0	0,3145	203				
2	300.2	298.2	0 2992	207				
3	294.4	294.9	0.2946	214	210		HAZ 2	
4	294.9	299.5	0,2972	210				
5	294,1	294,9	0,2945	214				
1	330,8	330,8	0,3308	169			n	
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				
Date:	06.11.22							
Tester:	Scheck							

Figure 3.50: Hardness measurements of 14HGS (7)

Order number 9039784000 Sample description 21 UN (1); Root Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H 2932-002-50430 Test conditions	\mathbb{N}		SRT	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Sample description 21 UN (1); Root Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions Image: Conditions Image: HW 10 DIN EN ISO 6506-1:2015-02 Image: HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+4-5) *C Test temperatur, if outside (23+4-5) *C Control 280,6 280,8 0,281 235 plate µm µm mm HV Distance in mm 1 326,0 325,5 0,3310 169 169 3 322,1 332,2 0,3310 169 169 169 1 322,6 336,0 0,3131 189 44312,0 140 312,2 0,3131 169 1	Order numb	er	9039784000	C.				
Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions	Sample desc	ription	21 UN (1);	Root				
Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions Colspan="4">Colspan="4"Colspan="4">Colspan="4">Colspan="4">Colspan="4"Colspan="	Administrate	or	Silcher					
Text and unmear Exercise 323 (neu) Serial number H2932-002-50430 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 6508-1:2016-12 Test temperatur, if outsile (23+/5) °C Reference: 237 HV 10 Indentation d1 d2 d4 Hardness Mean value Distance in mm Remark 1 326,0 325,5 0,3257 175	Tect instrum	ant	Zuiek 7 222	(2011)				
Serial number H2932-002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) *C Reference: 237 HV 10 Indentation no. d, d2 da, d4 Hardness Mean value HV Distance in mm Remark 1 326,0 325,5 0,325,5 0,325,7 175	rest instrum	ient	ZWICK Z 323	(neu)				
Test conditions HV 10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) °C Control plate 280,6 280,8 0,281 235 Mean value Distance in mm HV Bistance in mm Reference: 237 HV 10 Indentation no. d-1 326,0 325,5 0,3257 175 mm HV Distance in mm Remark 3 329,1 332,9 0,3310 169	Serial numbe	er	H2932-002-	50430				ter
Image: HV 10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/5) °C Control plate µm µm HRV Reference: 237 HV 10 Indentation no. d₁ d₂ d₄m Hardness Mean value Distance in mm Remark 1 326,0 325,5 0.3257 175	Test condition	ons						
HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+4.5) °C Control 280,6 280,8 0,281 235 Plate µm µm HW Reference: 237 HV 10 Indentation d₁ d₂ dm Hardness Mean value Distance in Remari 1 326,0 325,5 0,3257 175	🖸 HV	10	DIN EN ISO	6507-1:201	8-07			
HRC DIN EN ISO 6508-1:2016-12 Control 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation d1 d2 dm mm HV Distance in mm Reference: 237 HV 10 1 326,0 325,5 0,325,7 175 mm HV Distance in mm Remark 3 329,1 332,9 0,3310 169 169 169 BM 1 4 332,6 336,0 0,3343 166	HBW		DIN EN ISO	6506-1:201	5-02			
Initial Test temperatur, if outside (23+/5)*C Control plate 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation no. d, dz, d, dg, d, dg, generation Mean value Distance in mm Reference: 237 HV 10 1 326,0 325,5 0,3257 175 mm HV HV Distance in mm Remark 4 326,0 325,5 0,3257 175 Remark	HRC			6508-1-201	6_12			
Control plate 280,6 280,8 0,281 235 Reference: 237 HV 10 Indentation no. d1 d2 dm µm mm HV Mean value HV Distance in mm Remark 1 326,0 325,5 0,325,7 175 Distance in mm Remark 2 331,1 330,8 0,3310 169 169 Mean value Mean valu		Test temp	peratur, if out	side (23+4	5) °C			
plate µm µm mm HV Reference: 237 HV 10 Indentation d ₁ d ₂ d _m Hardness Mean value Distance in Remark 1 326,0 325,5 0,3257 175 2 331,1 330,8 0,3310 169 3 329,1 332,9 0,3310 169 <	Control	280.6	280.8	0,281	235			lesense pa
Indentation no. d ₁ µm d ₂ µm d _m mm Hardness HV Mean value HV Distance in mm Remark 1 326,0 325,5 0,325,7 175 175 175 175 175 175 175 175 169 160	plate	μm	μm	mm	HV		Reference:	237 HV 10
no. µm µm mm HV HV mm mm HV mm HV mm HV mm mm HV mm mm HV mm mm HV mm HV mm mm HV mm mm HX mm mm HX HX mm mm HX mm mm HX HX mm	Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark
Image: constraint of the second state of th	no.	μm	μm	mm	HV	HV	mm	Nemark
1 326,0 323,3 0,3237 173 2 331,1 330,8 0,3310 169 163 169 163 169 163 169 163 169 163 169 163 169 163 169 163 169 163 163 169 163 169 169 169 169 169 169 169 163 169 163 169 169 169 169 169 169 169 169 169 169 169 169 163 169 163		226.0	205.5	0.0057	475			
2 331,1 332,9 0,3310 109 169 169 BM 1 4 332,6 336,0 0,3343 166 169 1611 1611 169 1611 1611 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 169 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611 1611	1	320,0	325,5	0,3257	1/5			
3 332,6 336,0 0,3343 166 Image: constraint of the second	3	329.1	332.9	0,3310	169	169		
5 333,9 334,4 0,3342 166 1 317,3 319,4 0,3183 183 2 313,0 313,2 0,3131 189 3 307,4 312,0 0,3097 193 4 311,7 311,2 0,3115 191 5 313,2 313,2 0,3132 189 1 330,6 333,9 0,3233 168 2 329,8 331,9 0,3308 169 3 333,1 332,6 0,3297 171 5 332,9 330,8 0,3319 168 1 307,9 308,7 0,3083 195 2 308,1 308,7 0,3084 195 3 306,1 307,6 0,3084 195 3 306,1 307,6 0,3034 201 5 290,5 294,9 0,2927 216 1 339,3 336,2 0,3327 163 2 333,4 335,2 0,3343 166	4	332.6	336.0	0.3343	166			DIVI I
1 317,3 319,4 0,3183 183 2 313,0 313,2 0,3131 189 3 307,4 312,0 0,3097 193 4 311,7 311,2 0,3115 191 5 313,2 313,2 0,3132 189 1 330,6 333,9 0,3233 168 2 329,8 331,9 0,3308 169 3 333,1 332,6 0,3297 171 5 332,9 308,7 0,3083 195 2 306,1 307,6 0,3084 195 2 306,1 307,6 0,3084 195 3 306,1 307,6 0,3084 195 3 306,1 307,6 0,3034 201 5 290,5 294,9 0,2927 216 1 339,3 336,2 0,3311 169 169 2 333,4 335,2 0,3284 172 169 BM 2 3 325,2 326,3	5	333,9	334,4	0,3342	166			
2 313,0 313,2 0,3131 189 HAZ 1 3 307,4 312,0 0,3097 193 189 HAZ 1 4 311,7 311,2 0,3132 189 HAZ 1 5 313,2 313,2 0,3132 189 HAZ 1 1 330,6 333,9 0,3233 168 HAZ 1 2 329,8 331,9 0,3308 169 HAZ 1 3 333,1 332,6 0,3297 171 HAZ 1 5 332,9 330,8 0,3319 168 HAZ 1 1 307,9 308,7 0,3083 195 HAZ 2 2 308,1 308,7 0,3084 195 HAZ 2 3 306,1 307,6 0,3084 195 HAZ 2 3 306,1 307,6 0,3034 201 HAZ 2 1 339,3 336,2 0,3377 163 HAZ 2 2 333,4 335,2 0,3257 175 HAZ 2 3 303,3 <t< td=""><td>1</td><td>317,3</td><td>319,4</td><td>0,3183</td><td>183</td><td></td><td></td><td></td></t<>	1	317,3	319,4	0,3183	183			
3 307,4 312,0 0,3097 193 189 HAZ 1 4 311,7 311,2 0,3115 191 HAZ 1 5 313,2 313,2 0,3132 189 HAZ 1 1 330,6 333,9 0,3233 168 Image: Constant of the state of t	2	313,0	313,2	0,3131	189	1 1		
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 3 333,1 332,6 0,329 167 4 329,6 329,8 0,3297 171 5 332,9 330,8 0,3319 168 1 307,9 308,7 0,3083 195 2 308,1 308,7 0,3084 195 2 308,1 301,8 0,3034 201 HAZ 2 4 305,1 301,8 0,3034 201 HAZ 2 4 305,1 301,8 0,3034 201 HAZ 2 1 339,3 336,2 0,3377 163 HAZ 2 2 333,4 335,2 0,3343 166 HAZ 2 3 330,3 331,9 0,3311 169 HAZ 2 4 329,3 327,5 0,3284 172 HAZ 2	3	307,4	312,0	0,3097	193	189		HAZ 1
5 313,2 313,2 0,3132 189 1 330,6 333,9 0,3323 168 2 329,8 331,9 0,3308 169 3 333,1 332,6 0,3297 171 5 332,9 330,8 0,319 168 1 307,9 308,7 0,3083 195 2 308,1 308,7 0,3084 195 2 308,1 307,6 0,3084 195 2 308,1 301,8 0,3034 201 4 305,1 301,8 0,3034 201 5 290,5 294,9 0,2927 216 1 339,3 336,2 0,3311 169 1 339,3 335,2 0,3343 166 3 330,3 331,9 0,3311 169 169 BM 2 4 329,3 327,5 0,3257 175 5 325,2 326,3 0,3257 175 169	4	311,7	311,2	0,3115	191			
1 330,6 333,9 0,3323 168 2 329,8 331,9 0,3308 169 3 333,1 332,6 0,3329 167 4 329,6 329,8 0,3297 171 5 332,9 330,8 0,3319 168 1 307,9 308,7 0,3083 195 2 308,1 306,7 0,3084 195 2 306,1 307,6 0,3034 201 4 305,1 301,8 0,3034 201 5 290,5 294,9 0,2927 216 1 339,3 336,2 0,3311 169 1 339,3 336,2 0,3311 169 1 339,3 336,2 0,3257 163 2 333,4 335,2 0,3257 175 169 169 169 BM 2 4 329,3 327,5 0,3284 172 5 325,2 326,3 0,3257 175 Date:	5	313,2	313,2	0,3132	189			-
2 329,8 331,9 0,3308 169 169 WM 3 333,1 332,6 0,3297 171 169 WM 4 329,6 329,8 0,3297 171 169 HAZ 5 332,9 330,8 0,3319 168 168 169 HAZ 1 307,9 308,7 0,3083 195 2308,1 308,7 0,3084 195 2 308,1 307,6 0,3069 197 201 HAZ 2 4 305,1 301,8 0,3034 201 201 HAZ 2 5 290,5 294,9 0,2927 216 169 BM 2 1 339,3 336,2 0,3377 163 169 BM 2 2 333,4 335,2 0,3343 166 169 BM 2 3 330,3 327,5 0,3284 172 169 169 BM 2 4 329,3 327,5 0,3257 175 19 169 169 100 100	1	330,6	333,9	0,3323	168			
3 333,1 332,6 0,3329 167 169 VVM 4 329,6 329,8 0,3297 171 169 VVM 5 332,9 330,8 0,3319 168 1 169 169 169 1 307,9 308,7 0,3083 195 2308,1 306,7 0,3084 195 2 308,1 307,6 0,3069 197 201 HAZ 2 4 305,1 301,8 0,3034 201 201 HAZ 2 5 290,5 294,9 0,2927 216 163 169 BM 2 2 333,4 335,2 0,3343 166 169 BM 2 3 330,3 331,9 0,3311 169 169 BM 2 4 329,3 327,5 0,3284 172 169 169 169 169 Date: 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22 06.11.22	2	329,8	331,9	0,3308	169			
4 329,6 329,8 0,3297 171 5 332,9 330,8 0,3319 168 1 307,9 308,7 0,3083 195 2 308,1 308,7 0,3084 195 2 306,1 307,6 0,3069 197 3 306,1 307,6 0,3034 201 4 305,1 301,8 0,3034 201 5 290,5 294,9 0,2927 216 1 339,3 336,2 0,3343 166 3 330,3 331,9 0,3311 169 169 4 329,3 327,5 0,3284 172 169 BM 2 4 329,3 327,5 0,3284 172 169 169 BM 2 5 325,2 326,3 0,3257 175 175 169 169 169 169 169 169 169 169 169 169 169 169 169 169 169 169 169 169 169	3	333,1	332,6	0,3329	167	169		VVM
5 332,9 330,8 0,3319 168 1 307,9 308,7 0,3083 195 2 308,1 308,7 0,3084 195 3 306,1 307,6 0,3069 197 4 305,1 301,8 0,3034 201 5 290,5 294,9 0,2927 216 1 339,3 336,2 0,3377 163 2 333,4 335,2 0,3343 166 3 330,3 331,9 0,3311 169 BM 2 4 329,3 327,5 0,3284 172 0 Date: 06.11.22	4	329,6	329,8	0,3297	171			
1 307,9 306,7 0,3083 195 2 308,1 308,7 0,3084 195 3 306,1 307,6 0,3069 197 201 HAZ 2 4 305,1 301,8 0,3034 201 100 100 5 290,5 294,9 0,2927 216 100 100 1 339,3 336,2 0,3377 163 166 169 169 BM 2 3 330,3 331,9 0,3311 169 169 169 BM 2 4 329,3 327,5 0,3284 172 169	5	332,9	330,8	0,3319	168			
2 300,1 300,7 0,3004 195 201 HAZ 2 3 306,1 307,6 0,3069 197 201 HAZ 2 4 305,1 301,8 0,3034 201 100 100 5 290,5 294,9 0,2927 216 100 100 1 339,3 336,2 0,3377 163 166 169 169 169 BM 2 3 330,3 331,9 0,3311 166 169 169 BM 2 4 329,3 327,5 0,3284 172 169 <t< td=""><td>1</td><td>209.4</td><td>308,7</td><td>0,3083</td><td>195</td><td></td><td></td><td></td></t<>	1	209.4	308,7	0,3083	195			
4 305,1 301,8 0,3034 201	2	306.1	307.6	0,3064	195	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 4 329,3 327,5 0,3284 172 5 325,2 326,3 0,3257 175 Date: 06.11.22	3	305.1	301.8	0,3003	201	201		
1 339,3 336,2 0,3377 163 2 333,4 335,2 0,3343 166 3 330,3 331,9 0,3311 169 4 329,3 327,5 0,3284 172 5 325,2 326,3 0,3257 175 Date: 06.11.22	4	290.5	294.9	0.2927	216			
2 333,4 335,2 0,3343 166 3 330,3 331,9 0,3311 169 169 4 329,3 327,5 0,3284 172 5 325,2 326,3 0,3257 175 Date: 06.11.22	1	339.3	336.2	0.3377	163			
3 330,3 331,9 0,3311 169 169 4 329,3 327,5 0,3284 172 5 325,2 326,3 0,3257 175	2	333.4	335.2	0.3343	166		-	
4 329,3 327,5 0,3284 172 5 325,2 326,3 0,3257 175 Date: 06.11.22	3	330.3	331.9	0,3311	169	169		BM 2
5 325,2 326,3 0,3257 175 Date: 06.11.22	4	329,3	327,5	0,3284	172			
Date: 06.11.22	5	325,2	326,3	0,3257	175			
Date: 06.11.22		-		-				
Tester: Scheck	Date: Tester:	06.11.22 Scheck						

Figure 3.51: Hardness measurements of 14HGS (8)

\mathbb{N}				Test rep PAS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	21 UN (1), C	uter layer					
Administrate	or	Silebor				P. C. S. A. B.		
Test Instance								
rest instrum	ient	Zwick Z 323	(neu)					
Serial number	er	H2932-002-	50430					
Test condition	ns							
🖸 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 ou	utside (23+	45) *C				
Control	280,6	280,8	0,281	235		Patarana		
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	Nemork	
4	211.2	214.0	0 2121	100			-	
2	311,3	314,9	0,3131	186				
3	311.8	314.9	0,3133	189	185	-	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				
3	294,7	302,0	0,2984	208	198		HAZ 1	
4	298,9	294,5	0,2967	211				
5	302,4	299,5	0,3010	205				
1	319,2	320,9	0,3201	181				
2	324,0	324,4	0,3242	1/0	170		\//М	
3	321.5	311.3	0,3164	185	175			
5	330.2	327.9	0.3291	171				
1	298,5	295,8	0,2971	210				
2	303,9	303,5	0,3037	201				
3	297,6	296,0	0,2968	210	205		HAZ 2	
4	305,1	307,2	0,3062	198				
5	298,7	298,3	0,2985	208				
1	332,3	332,1	0,3322	168				
2	324.0	324.6	0,3310	176	174		BM 2	
3	319.5	326.9	0.3232	178	174			
5	325,1	321,1	0,3231	178				
				2000 (102-200) 2		-		
Date: Tester:	06.11.22 Scheck							

Figure 3.52: Hardness measurements of 14HGS (9)

\mathbb{N}	STUTTGA		MP	Test rep AS-PPB 523 Hardness	oort 10-08/1 test	Re Metallo Elektrone	e ferat ographie und enmikroskopie
Order numb	er	9039784000					
Sample desc	ription	21 UN (1);	Root				
Administrate	or	Silcher					
Test instrum	ient	Zwick Z 323	(neu)				
Serial number	er	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			
	Test tem	peratur, if ou	tside (23+/-	-5) °C			
Control	280,6	280.8	0.281	235		D -6	
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	Action
				100			
1	318,2	318,2	0,3182	183			
2	327,3	326,9	0,3271	173	160		
3	335,8	332,9	0,3344	160	100		BM 1
4	330.6	343,3	0,3428	160			1
1	335.0	337.7	0,3404	164			
2	331.5	328.6	0,3300	170			1
3	325.9	326.9	0.3264	174	172		
4	321.3	319.0	0.3202	181			
5	326.7	327.5	0.3271	173			1
1	339.6	335.4	0.3375	163			
2	337.5	336.7	0.3371	163			1
3	332,5	335,2	0,3339	166	162		WM
4	337,9	339,2	0,3385	162			1
5	343,9	345,0	0,3444	156			1
1	328,8	324,8	0,3268	174			
2	328,6	328,8	0,3287	172			
3	332,1	328,8	0,3304	170	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			4
2	327,1	331,3	0,3292	1/1	474		
3	328,2	324,6	0,3264	1/4	174		BM 2
4	310.4	325.2	0,3220	178			4
5	515,4	323,3	0,5224	170			
Date: Tester:	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
[%]	0.18	0.2	1.57	0.007	0.001	0.02	0.05	0.01
	Ni	V	Ti	Nb				
	0.58	0.18	0.001	0.002				

Table 3.48: Fracture toughness of WSTE 420

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

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

Only the base material was investigated.

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



Figure 3.54: Crack growth WStE 420

3.16 St53.7

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

The base material has the following properties:

Table 3.49: Characteristics of St53.7

Production year	1972	
Production standard	DIN 17172	
Specific minimum characteristics	R _e [MPa]	363
	R _m [MPa]	510
	K _v /A [kgm/cm ²] ¹¹	4
Material characteristics	R _e [MPa]	381
	R _m [MPa]	560
	K _v /A [kgm/cm ²] ¹¹	8,8

Table 3.50: Chemical composition of St53.7

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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}			MF	Test rep AS-PPB 523 Hardness	oort 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	l.				
Sample descr	iption	19.1; Outer	layer				
Administrato	r	Silcher					The second states
Tort instrum		Twick 7 323	(0011)				
Corial number		L2022 002	(iieu)				
Serial numbe		H2932-002-	50450				
Test conditio	ns						
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			및 별시험 등법 (중가), ⁴ 8
	Test ten	peratur, if ou	utside (23+	45) °C			
Control	280.6	280.8	0.281	235		1280	
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark
no. 🛄	μm	μm	mm	HV	HV	mm	Remork
- 1	210 5	200.7	0.2101	102			
2	318.0	315.3	0,3166	195			
3	319,0	317,2	0,3181	183	185		
4	315,7	318,8	0,3173	184			
5	321,1	324,2	0,3227	178			
1	284,8	288,3	0,2865	226			
2	287,9	289,3	0,2886	223			
3	284,8	284,8	0,2848	229	223		HAZ 1
4	292,7	292,3	0,2925	217			
5	292,0	288,7	0,2904	220			-
2	309,3	304,5	0,3009	197			
3	312.2	307.6	0,3028	193	192		10/04
4	312.6	311.1	0.3119	191	102		VVIVI
5	322.8	321.5	0.3221	179			
1	301.4	302.6	0.3020	203			
2	287,5	286,9	0,2872	225			
3	287,1	288,9	0,2880	224	220		HAZ 2
4	283,1	283,5	0,2833	231			
5	292,5	290,0	0,2912	219			
1	321,5	322,3	0,3219	179			
2	316,9	323,6	0,3203	181	101		
3	315,3	319,9	0,31/6	184	181		BM 2
5	317.8	322.8	0,3203	181			
5	517,0	022,0	0,0200	101			
Date: Tester:	06.11.22 Scheck						

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

\square			MF	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000					
Sample descr	iption	19.1; Root	E.			a strategies	ET AD
Administrato	r	Cilahan					
		Silcher					
Test instrum	ent	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	이 안 많다. 그		
	Test tem	peratur, if out	side (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference	227 111/ 40
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	Stational .
1	320.9	318.4	0.3196	181			
2	318.8	321.9	0.3204	181			•
3	320.7	323.4	0.3220	179	179		BM 1
4	321,5	325.0	0,3233	177			2
5	324,4	323,6	0,3240	177			
1	334,8	337,7	0,3363	164			
2	327,9	323,0	0,3255	175			
3	330,6	327,3	0,3290	171	171		HAZ 1
4	330,0	328,2	0,3291	171			
5	327,9	326,3	0,3271	173			
1	315,1	312,8	0,3139	188			
2	319,0	316,5	0,3178	184			
3	325,7	321,5	0,3236	177	180		VVM
4	324,0	323,2	0,3236	177			
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		11470
3	315,7	314,5	0,3151	187	183		
4	317,0	312,8	0,3149	187			
5	372.0	309,5	0,3100	192		2	
2	323,0	320,1	0,3244	175			
2	323,2	326,2	0,3237	173	177		BM 2
ک	319.6	325.5	0,3241	178			
	313.8	327.9	0.3209	180			
	515,6	021,0	5,0200				
Date: Tester:	06.11.22 Scheck						

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

\geq			MP	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie
Order numb	er	9039784000	1				
Sample descr	iption	19.2; Outer	layer			And Alexandre	
Administrato	r	Cileber	and the second	0			
		Silcher					
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		ACE	- and the second second
HBW		DIN EN ISO	6506-1.201	5-02			
- HRC			6500 1.201	6 42			
	CONTRACTOR OF	DIN EN ISO	0508-1:201	0-12			
	Test tem	peratur, if our	tside (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	2012/02/02/02
1	312.0	31/ 7	0 3133	189			
2	311.8	317.8	0.3148	187			1
3	313.8	319.0	0.3164	185	185		BM 1
4	318,2	318,8	0,3185	183			1
5	320,7	320,1	0,3204	181			
1	317,8	317,8	0,3178	184			
2	302,2	305,3	0,3038	201	10.00		
3	307,2	307,6	0,3074	196	192		HAZ 1
4	311,3	310,5	0,3109	192			
5	314,9	314,7	0,3148	187			
1	321,1	322,8	0,3219	179			
2	322,1	320,7	0,3214	180	470		WM
3	340,0	332,7	0,3364	104	178		
4	317,0	316,5	0,3171	195			
1	296.2	296.2	0,3107	211			
2	294.8	294.9	0 2948	213			
3	294.7	295.4	0.2951	213	210		HAZ 2
4	300.8	298.5	0.2996	207			
5	298,7	299,3	0,2990	207			1
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		BW 5
4	309,7	316,1	0,3129	189			
5	308,0	313,2	0,3106	192		-	
Date: Tester:	06.11.22 Scheck						

Figure 3.58:	Hardness	measurements	of	X56.7	(3))
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			MF	Test report MPAS-PPB 52310-08/1 Hardness test			e ferat graphie und enmikroskopie
Order numb	er	9039784000					-
Sample desc	ription	19.2; Root		-		The second	
Administrate	or	Silcher				-	
Toot instaurs		Tudek 7 202	(0011)				
rest instrum	lent	ZWICK Z 323	(neu)	100			
Serial numbe	er	H2932-002-	50430				
Test conditio	ons					-	
I HV	10	DIN EN ISO	6507-1:201	8-07		a parts	
HBW			6506-1.201	5-02			
			0300-1.201	5-02			
HRC	120100-0402-040	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			2.57 110 10
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark
no.	μm	μm	mm	HV	HV	mm	201030107052
	210.0	221.1	0 2204	101			
2	318.4	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	100000000 (L		
5	325,2	326,5	0,3259	175			
0	245 2	312,4	0,3138	188			1
1	315,3		0 3110	191	I I		
1	315,3	311,3	0,5115	400	188		
1 2 3	315,3 312,4 316,1	311,3 312,8	0,3145	188	188	-	HAZ 1
1 2 3 4	315,3 312,4 316,1 314,3 315,0	311,3 312,8 313,8 319,0	0,3145 0,3140	188 188	188	-	HAZ 1
1 2 3 4 5	315,3 312,4 316,1 314,3 315,9 306,6	311,3 312,8 313,8 318,0 303,5	0,3145 0,3140 0,3169 0,3050	188 188 185 199	188		HAZ 1
1 2 3 4 5 1 2	315,3 312,4 316,1 314,3 315,9 306,6 303 7	311,3 312,8 313,8 318,0 303,5 297 4	0,3145 0,3140 0,3169 0,3050 0,3006	188 188 185 199 205	188		HAZ 1
1 2 3 4 5 1 2 3	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296.2	311,3 312,8 313,8 318,0 303,5 297,4 290,6	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934	188 188 185 199 205 215	280		HAZ 1
1 2 3 4 5 1 2 3 4	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186	188 185 199 205 215 388	188 280		HAZ 1
1 2 3 4 5 1 2 3 4 3 4 5	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175	188 185 199 205 215 388 392	280		HAZ 1
1 2 3 4 5 1 2 3 4 2 3 4 5 1	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 216,9 218,0 314,9	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138	188 185 199 205 215 388 392 188	280		HAZ 1 WM
1 2 3 4 5 1 2 3 4 4 5 1 2 3 1 2 2 3	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0 314,9 308,0	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,3108	188 185 199 205 215 388 392 188 192	280		HAZ 1 WM
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 3 3 4 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0 314,9 308,0 305,5	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,3108 0,3047	188 188 185 199 205 215 388 392 188 192 200	188 280 198		HAZ 1 WM HAZ 2
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 4 5 1 2 3 4 4 5 5 1 2 3 4 4 5 5 1 2 3 3 5 5 1 2 3 5 5 5 1 2 3 1 2 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9 299,3 201,2	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0 314,9 308,0 305,5 297,2 207,2	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,3108 0,3047 0,2983	188 188 185 199 205 215 388 392 188 192 200 208	188 280 198		HAZ 1 WM HAZ 2
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 5 1 1 2 3 3 4 5 5 1 1 2 3 3 1 1 2 3 3 1 1 2 3 3 1 1 2 3 3 1 1 2 3 1 1 2 3 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 2 3 1 2 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 3 3	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9 299,3 304,3 217,4	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0 314,9 308,0 305,5 297,2 302,2 216,1	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,2175 0,3138 0,3108 0,3047 0,2983 0,3033 0,3033	188 188 185 199 205 215 388 392 188 192 200 208 202	188 280 198		HAZ 1 WM HAZ 2
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9 299,3 304,3 312,4 314,2	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 216,9 218,0 314,9 308,0 305,5 297,2 302,2 316,1 317,8	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,3108 0,3047 0,2983 0,3047 0,2983 0,3047	188 185 199 205 215 388 392 188 192 200 208 202 188 188 192	188 280 198		HAZ 1 WM HAZ 2
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9 299,3 304,3 312,4 314,2 305,3	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0 314,9 308,0 305,5 297,2 302,2 316,1 317,8 313,4	0,3145 0,3140 0,3169 0,3050 0,2934 0,2186 0,2175 0,3138 0,2175 0,3138 0,3108 0,3047 0,2983 0,3047 0,2983 0,3033 0,3143 0,3160 0,3094	188 188 189 205 215 388 392 188 192 200 208 202 188 192	188 280 198		HAZ 1 WM HAZ 2
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 4 5 1 2 3 4 4 5 1 2 3 4 4 5 5 1 2 3 4 4 5 5 1 2 3 4 5 5 1 1 2 3 3 4 5 5 1 1 2 3 3 4 5 5 1 1 2 3 3 4 5 5 1 1 2 3 3 1 2 3 3 3 4 5 5 5 1 1 2 3 3 3 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9 299,3 304,3 312,4 314,2 305,3 302,2	311,3 312,8 313,8 313,8 303,5 297,4 290,6 216,9 218,0 314,9 308,0 305,5 297,2 302,2 302,2 316,1 317,8 313,4 304,9	0,3145 0,3140 0,3169 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,3108 0,3047 0,2983 0,3047 0,2983 0,3033 0,3143 0,3160 0,3094 0,3036	188 188 185 199 205 215 388 392 188 192 200 208 202 188 192 200 208 202 188 186 194 201	188 280 198 192		HAZ 1 WM HAZ 2 BM 2
1 2 3 4 5 1 2 3 4 4 5 1 2 3 4 5 1 2 3 4 5 5 1 2 3 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	315,3 312,4 316,1 314,3 315,9 306,6 303,7 296,2 220,3 217,0 312,8 313,6 303,9 299,3 304,3 312,4 314,2 305,3 302,2 308,2	311,3 312,8 313,8 318,0 303,5 297,4 290,6 216,9 218,0 314,9 308,0 305,5 297,2 302,2 302,2 316,1 317,8 313,4 304,9 312,2	0,3145 0,3145 0,3140 0,3050 0,3006 0,2934 0,2186 0,2175 0,3138 0,3108 0,3047 0,2983 0,3047 0,2983 0,3033 0,3143 0,3160 0,3094 0,3036 0,3102	188 188 185 199 205 215 388 392 188 192 200 208 202 188 192 200 208 202 188 194 201 193	188 280 198 192		HAZ 1 WM HAZ 2 BM 2

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

Chamies Learne sitism	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.2	0.32	1.36	0.03	0.02	0.09	0.08	0.01
	Ni	V	Ti	Nb		•	<u>.</u>	<u>.</u>
	0.04	0.01	0.01	0.01				

Table 3.54: Fracture toughness of X56.7

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

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

- 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	RT	MP	Test rep AS-PPB 523 Hardness	oort 10-08/1 test	Re Metallo Elektrone	eferat ographie und ienmikroskopie	
Order numb	er	9039784000						
Sample descr	iption	12.1-LN Ou	ter layer					
Administrato	or	Silcher		Reality			Contraction of the last	
Tect Instrum		Zwiek 7 222	(nou)					
rest instrum	ent	ZWICK Z 323	(neu)					
Serial numbe	er	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				
			0000 1.201	0.40				
	1000 (100) (1000 (1000 (100) (1000 (100) (100) (1000 (100) (1000 (100) (100) (1000 (100) (1000 (100) (100) (1000 (100) (DIN EN ISO	0508-1:201	0-12				
	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				
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	10100005000	
1	296.2	293.1	0 2946	214				
2	293,1	292,9	0,2930	216	218			
3	288,5	288,9	0,2887	222			BM 1	
4	288,8	292,1	0,2904	220				
5	292,7	292,2	0,2925	217				
1	272,7	270,9	0,2718	251				
2	275,3	274,6	0,2749	245				
3	268,8	269,2	0,2690	256	246	2	HAZ 1	
4	279,8	277,5	0,2786	239				
5	280,2	276,3	0,2782	240				
1	275,6	273,8	0,2747	246				
2	277,3	278,8	0,2780	240			10/64	
3	279,4	280,6	0,2800	237	240		VVIVI	
4	279,0	275,4	0,2772	241				
5	2/9,8	280,4	0,2801	236				
2	200,0	207,1	0,2079	250				
2	270,5	273.6	0,2720	201	250		HA7 2	
3	270.2	275.0	0 2726	240	230			
5	274.2	276.3	0.2752	245				
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	1000000000000			
5	299,9	297,2	0,2986	208				
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}			MP	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	12.1-LN Cer	nter					
Administrato	or	Silcher			Contraction of the Contraction	1 and the		
Test Instrum		7	(min)					
Test Instrum	ent	ZWICK Z 323	(neu)				And the second second	
Serial numbe	≥r	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				
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		Rafarance	227 111/ 40	
plate	μm	μm	mm	HV		neierence.	237 HV 10	
Indentation	d1	dz	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	100000000	
	0447	040.7	0.0457	100				
1	314,7	316,7	0,3157	186				
2	312.0	311.5	0,3177	104	101		BM 1	
4	304.9	305.1	0,3050	199	101			
5	308.6	307.2	0.3079	196				
1	284.1	283,5	0.2838	230				
2	282,7	279,6	0,2811	235	1 1		HAZ 1	
3	285,4	283,9	0,2847	229	223			
4	287,7	289,1	0,2884	223				
5	302,6	305,5	0,3041	201				
1	292,2	287,5	0,2899	221				
2	293,1	290,6	0,2918	218			10/11/1	
3	296,4	296,4	0,2964	211	214		V V I V I	
4	298,3	293,5	0,2959	212				
5	298,9	300,1	0,2995	207		-		
1	276,3	279,2	0,2777	240				
2	277,9	277,1	0,2775	241	024		HAZ 2	
3	274,0	270,7	0,2756	244	231			
4	200,5	290,0	0,2695	221				
5	317.9	237,4	0,2990	183	-			
2	313.8	312.8	0.3133	189				
2	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				
	1							
Date: Tester:	06.11.22 Scheck	-						

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

\mathbb{N}				Test rep AS-PPB 523 Hardness	0 0rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie	
Order numbe	er	9039784000)				
Sample descri	iption	12.1-LN R	oot				
Administrato		Silcher				Contraction and	And the second second
T	51. 1990 (2011)	7	()				
lest instrume	int	ZWICK Z 323	(neu)			See Star	
Serial number	r	H2932-002-	50430				
Test condition	ns						
П HV 1	10	DIN EN ISO	6507-1:201	8-07			
HBW		DIN EN ISO	6506-1.201	5-02			
			0000 1.201	0.40			
	Test ten	DIN EN ISO	0508-1.201	6-12 45) *C			
	000.0			-5) 0		1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1	· · · · · · · · · · · · · · · · · · ·
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	µm.	<u>µm</u>	- mm	riv I I I I I I I I I I I I I I I I I I I	Marine status	Distance in	
Indentation	a1	0 ₂	a _m	Hardness	Mean value HV	Distance in	Remark
110.	huit	- priv					
1	295,8	299,1	0,2974	210			
2	293,7	298,3	0,2960	212			
3	291,6	297,2	0,2944	214	212		BM 1
4	292,0	297,6	0,2948	213			
5	292,9	301,6	0,2972	210			
1	304,9	305,5	0,3052	199	I		
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	1 1		
5	276,5	278,4	0,2774	241			
1	287,9	287,3	0,2876	224			
2	286,2	286,4	0,2863	226			
3	283,9	280,0	0,2820	233	228		WM
4	286,2	284,2	0,2852	228	1 1		
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	281,5	0,2822	233			
2	299,7	302,4	0,3011	205		-	
2	293,5	290,9	0,2962	211	200		DMO
3	292,5	290,2	0,2943	214	209		BM2
5	298.3	305.1	0.3017	204	1 I		
	200,0		0,0011	201			
Date: (Tester: ()6.11.22 Scheck	•					

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

\mathbb{N}	STUTTG?		M	Test rep PAS-PPB 523 Hardness	00rt 110-08/1 5 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)					
Sample desc	ription	12.2-LN Ou	ter laver					
Administrate	ar	Cilahan	o a sa s		-	A store of the second	A DAY STORE	
Aummiscieu		Slicher						
Test instrum	ient	Zwick Z 323	(neu)					
Serial numbe	er	H2932-002-	50430			A strange of the		
Test conditio	ons							
U HV	10	DIN EN ISO	6507-1:201	8-07		Part of the second seco		
HBW		DIN EN ISO	6506-1:201	5-02				
HRC		DIN EN ISO	6508-1-201	6-12				
	Test tem	peratur, if ou	itside (23+/	45) °C				
Control 280.6 280.8			0.281	235		02284	CONTRACT OF CONTRACT.	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	d _m	Hardness HV	Mean value HV	Distance in mm	Remark	
	Parte	pan						
1	302,8	296,8	0,2998	206	-	1		
2	297,6	298,1	0,2979	209		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		ę	HAZ 1	
2	282,9	274,2	0,2786	239	227			
3	270,9	2/0,1	0,2775	241	237	1		
4	281.7	279.6	0,2821	235				
1	282.1	280.8	0.2815	234				
2	285.8	281.9	0.2838	230				
3	286,6	284.4	0,2855	227	231		WM	
4	282,3	282,7	0,2825	232				
5	285,2	282,7	0,2840	230				
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		-		
5	280,6	2//,1	0,2789	238		b	G	
1	208.0	207.4	0,3041	201				
2	302.2	300.5	0.3014	203	204			
4	301.4	301.0	0.3012	204	204		BIVI 2	
5	302,0	302,4	0,3022	203				
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallo Elektrone	g raphie und enmikroskopie
Order numb	er	9039784000	e.				
Sample desc	ription	12.2-LN Ce	nter			CONTRACTOR	
Administrate	or	Silcher				Sagli Bar	
Tect instrum	ant	Zuiek 7 222	(2011)				
Test instrum	ient	ZWICK Z 323	(neu)				
Serial number	er	H2932-002-	50430			2. martilla	
Test conditio	ons				and the second second		
I HV	10	DIN EN ISO	6507-1:201	8-07			
			6E06 1:201	5 02			
		DIN EN 150	0500-1.201	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		Pafarance	22710/40
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	Action
	045.4	217.0	0.0104	105			
1	315,1	317,8	0,3164	185			
3	313.2	314,5	0,3100	190	188		BM 1
4	313.0	312.6	0.3128	190	100		
5	311.3	309.5	0.3104	192			
1	282,1	279,6	0,2808	235			
2	284,8	285,4	0,2851	228			
3	288,9	287,9	0,2884	223	215		HAZ 1
4	307,2	305,1	0,3062	198			
5	308,6	310,3	0,3095	194	·		
1	288,3	286,6	0,2875	224			
2	290,6	288,3	0,2895	221	214		10/10/1
3	292,5	287,9	0,2902	220	214		VVIVI
4	302,0	299,7	0,3012	204			
1	285.6	283.3	0,2845	229			
2	285.0	285,8	0.2854	228			
3	286,4	285,6	0,2860	227	220		HAZ 2
4	298,9	296,4	0,2976	209			
5	300,1	299,3	0,2997	206			
1	320,7	321,1	0,3209	180			
2	318,8	316,5	0,3177	184			5.4.6
3	315,5	312,6	0,3140	188	187		BM 2
4	313.9	309,3	0,3093	194		-	
5	515,0	512,0	0,0100	103			
Date: Tester:	06.11.22 Scheck						

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

V				Test rep PAS-PPB 523 Hardness	oort 10-08/1 5 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	12.2-LN R	oot					
Administrate	or	Silcher				and the second		
To at London		Zuriale 7 222	(2011)					
Test instrum	ient	ZWICK Z 323	(neu)					
Serial number	er	H2932-002-	50430			Anna Maria		
Test conditio	ons			-	West Constant of the			
ы ни	10	DIN EN ISO	6507-1.201	8-07				
	10		0507-1.201	5.00				
L 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		Pafaranca	00710/40	
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	Nemark	
1	301,6	300,5	0,3011	205				
2	302,0	303,9	0,3029	202	206			
3	296,4	300,8	0,2986	208	206		BM 1	
5	297.2	300.6	0,2989	208		-	1	
1	289.1	286.2	0.2877	224				
2	286,4	289,8	0,2881	223	1 1		HAZ 1	
3	294,9	292,9	0,2939	215	215			
4	293,9	299,1	0,2965	211		_		
5	304,5	302,8	0,3037	201				
1	300,1	302,4	0,3013	204				
2	302,2	302,8	0,3025	203				
3	300,1	299,9	0,3000	206	202		V V IVI	
4	300,2	306,4	0,3073	200				
1	307.6	306.4	0,3070	197				
2	299.3	295.6	0.2974	210				
3	297,0	298,1	0,2975	209	209		HAZ 2	
4	294,5	292,9	0,2937	215			1	
5	293,9	291,6	0,2928	216				
1	310,3	310,7	0,3105	192				
2	304,1	307,4	0,3057	198	204			
3	300,8	302,2	0,3015	204	201	-	BIM 2	
4	298.5	301,8	0,2999	205			1	
<u>J</u>	200,0		0,2000	200				
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}			MF	Test rep AS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	12.1-UN Ou	ter layer				and the second	
Administrato	or	Silcher		-				
To at Instances		7	(= =)					
lest instrum	ent	ZWICK Z 323	(neu)					
Serial numbe	er	H2932-002-	50430					
Test conditio	ns							
I HV	10	DIN EN ISO	6507-1:201	8-07				
			6506 1.201	5.02				
			0000-1.201	J-02				
HRC		DIN EN ISO	6508-1:201	6-12				
	Test temp	peratur, if out	side (23+1-	5) °C				
Control	280,6	280,8	0,281	235		Reference:	227 HV 40	
plate	μm	μm	mm	HV		Herefeller	237 11 10	
Indentation	d,	d2	d _m	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	2010/02/02/02	
1	305.3	308.4	0 3060	107				
2	305,5	308.6	0,3009	197				
3	304.7	305.1	0.3049	199	197		BM 1	
4	306.4	310,1	0,3082	195				
5	305,7	309,7	0,3077	196			1	
1	296,4	295,8	0,2961	212				
2	285,0	286,9	0,2859	227]	
3	284,0	292,0	0,2880	224	221		HAZ 1	
4	287,6	285,8	0,2867	226				
5	294,3	294,2	0,2943	214				
1	308,0	303,0	0,3055	199				
2	305,9	304,7	0,3053	199	100		1.0/6.4	
3	314,5	315,7	0,3151	187	188		VVIVI	
4	314,1	314,7	0,3144	188				
5 1	201.0	331,5	0,3319	221				
2	286.6	201,1	0,2094	221			1	
2	286.9	287.7	0.2873	225	222	-	HA7 2	
4	290.6	291.6	0,2911	219				
5	289.6	287.3	0,2884	223			1	
1	304,3	312,6	0,3084	195				
2	306,3	314,5	0,3104	192			1	
3	303,7	312,6	0,3081	195	196		BM 2	
4	304,1	306,8	0,3054	199			1	
5	302,0	310,3	0,3062	198				
Date: Tester:	06.11.22 Scheck						1	

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

\mathbb{N}	STUTTGA	SRT	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000	ĺ					
Sample descr	iption	12.1-UN R	oot					
Administrato	r	Cilabor						
			a warana wa					
lest instrum	ent	Zwick Z 323	(neu)	the second				
Serial numbe	r	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				
L HBC			6509 1:201	6 12				
	Test temr	peratur if out	side /23+L	5) *C				
	1000 C		0 004	205		1040cav	These services and these	
Control	280,6	280,8	0,281	235		Reference:	237 HV 10	
Indontation	d.	d.	d	nv.	Maan yaha	Distance in		
no.	μm	um	mm	HV	HV	mm	Remark	
1	303,9	309,5	0,3067	197				
2	303,7	307,6	0,3056	199	194		514 /	
3	305,1	310,1	0,3076	196			BM 1	
4	309,1	312,2	0,3106	192				
5	313,6	317,6	0,3156	186				
1	317,4	316,3	0,3169	185				
2	318,4	319,0	0,3187	183	170			
3	324,2	323,2	0,3237	170	1/9		HAZ 1	
4	322,3	323,0	0,3230	170				
1	313 /	311 3	0,3290	190				
2	315.3	312.8	0,3124	188				
2	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				
2	322.3	326,3	0,3243	176				
3	313,6	323,0	0,3183	183	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				
3	314,5	323,4	0,3189	182	184		BM 2	
4	314,0	320,3	0,3172	184				
5	308,4	319,7	0,3140	188				
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}			MP	Test rep AS-PPB 523 Hardness	10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	12.2-UN Ou	ter layer			Westerner States		
Administrato	or	Silcher						
Tect instrum	ant	Twick 7 222	(nou)					
Test instrum	ent	ZWICK Z 323	(neu)					
Serial numbe	ber H2932-002-50430					and the second of the		
Test conditio	ins							
I HV	10	DIN EN ISO	6507-1:201	8-07				
HBW		DIN EN ISO	6506-1:201	5-02				
HRC			6508 1:201	6.12				
	Test tem	peratur if ou	tside (23+4	-5) °C				
Control	280.6	280.8	0.281	235		284	Restriction.	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Domaste	
no.	μm	μm	mm	HV	HV	mm	Kenidik	
	040.0	010.0	0.0404	400				
1	313,0	319,3	0,3161	186				
2	305.7	309.7	0,3119	196	192			
4	305.5	313.8	0.3097	193	132		DIVI	
5	308,0	310,5	0,3093	194				
1	291,4	293,3	0,2924	217				
2	285,8	286,2	0,2860	227	10.0000			
3	284,4	286,4	0,2854	228	226		HAZ 1	
4	280,6	286,9	0,2838	230				
5	284,4	284,0	0,2845	193				
2	316.5	312.6	0,3146	187				
3	310.1	300.5	0.3053	199	190		WM	
4	312.2	307.8	0.3100	193	1000			
5	316,5	313,2	0,3149	187				
1	300,5	297,8	0,2992	207				
2	289,3	288,1	0,2887	222	(12/10/27)		1147.0	
3	281,9	281,7	0,2818	234	218		HAZ 2	
4	290,4	288,3	0,2893	222				
5	299,3	299,1	0,2992	186				
2	312.8	316.7	0.3148	187				
3	310.3	309.9	0.3101	193	191		BM 2	
4	310,1	311,1	0,3106	192	0.000			
5	304,3	309,3	0,3068	197				
Date:	06.11.22							
Tester:	Scheck							

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

			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000	ĺ.					
Sample desc	ription	12.2-UN R	oot			The second second		
Administrate	or	Silcher						
Test instrum	ent	Zwick 7 323	(neu)					
Serial numb	er	L2022 002	(neu)					
Techonodiate		H2932-002-	50450		(in the second			
	ons							
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		Reference: 00710440		
plate	μm	μm	mm	HV		Neterence.	237 HV 10	
Indentation	d,	d₂	d _m	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	2010/2020/05/2	
1	315.2	326.3	0 3207	180				
2	309.7	320,5	0,3153	187				
3	313.2	316.9	0.3151	187	187		BM 1	
4	306,6	315,1	0,3108	192				
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			-	
2	313 /	325,0	0,3200	1/5				
2	318.4	315.3	0.3168	185	178		WM	
4	332.1	330.2	0.3312	169	175			
5	331.3	328,4	0.3298	170				
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	313,0	317,4	0,3155	100	190		BM 2	
3	307.8	312.2	0,3139	100				
5	303,5	309,7	0,3066	197				
Date: Tester:	06.11.22 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

Chamies Learne sitism	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.17	0.29	1.39	0.02	0.011			
	Ni	V	Ti	Nb		•	•	•
		0.06						

Table 3.57: Fracture toughness of St60.7

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

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

- 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.

			MF	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie					
Order numb	er	9039784000	ř.								
Sample desc	ription	6.1; Outer	6.1; Outer layer								
Administrato	or	Silcher	Silcher								
Tact instrum	ant	7	(
rescustrum	ent	ZWICK Z 323	Zwick Z 323 (neu)								
Serial numbe	er	H2932-002-	50430								
Test conditio	ns			Contest							
U HV	10	DIN EN ISO	6507-1:201	8-07							
HRW			6506 1:201	5.02							
			0300-1.201	5-02							
HKC		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: 227 HV 10						
plate	μm	μm	mm	HV			257 114 10				
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark				
no.	μm	μm	mm	HV	HV	mm	2010/02/2010/2				
	260.2	271.0	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	1 -						
5	279,6	279,0	0,2793	238							
1	258,4	258,8	0,2586	277							
2	249,9	254,5	0,2522	292							
3	245,4	262,7	0,2540	287	279		HAZ 1				
4	251,8	254,0	0,2529	290							
5	2/1,9	272,1	0,2720	251			-				
2	302,0	305,0	0,3039	176							
2	320,3	320.1	0,3202	181	187		WM				
4	307.4	305.1	0.3063	198			1				
5	323.8	323.0	0,3234	177							
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	288,5	0,2899	221							
1	292,0	292,5	0,2923	217							
2	290,0	200,9	0,2894	221	221		BM 2				
3	289.8	288.9	0.2893	224	221						
5	288.1	292,2	0,2902	220							
Date: Tester:	06.11.22 Scheck										
Testel.	Scheck										

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

STUTTGART			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie					
Order numb	er	9039784000									
Sample desc	ription	6.1; Root	6.1; Root								
Administrato	or	Silcher	Silcher								
Tact Instrum		7									
rest instrum	ent	ZWICK Z 323	Zwick Z 323 (neu)								
Serial numbe	er	H2932-002-	50430								
Test conditio	ns										
I HV	10	DIN EN ISO	6507-1:201	8-07							
			6506 1:201	5.02							
		DIN EN 150	0500-1.201	5-02							
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 007 uni 44						
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	Kenidik				
1	280,0	286,0	0,2830	232							
2	279,6	280,0	0,2798	237	220						
3	280,8	283,3	0,2821	233	229		DIVI I				
4	204,2	290,2	0,2872	225							
1	200,5	294,5	0,2915	100							
2	304,5	302.6	0,3030	204							
3	302.6	303.9	0.3033	204	201		HA7 1				
4	302.0	302.8	0.3024	203	201	-					
5	305.7	306.4	0 3061	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	1	WM				
4	329,2	326,7	0,3279	172							
5	326,9	328,6	0,3277	173							
1	312,6	313,4	0,3130	189							
2	307,6	306,6	0,3071	197							
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	295,4	0,2951	213							
2	294,7	294,9	0,2948	213	216						
3	290,0	293,5	0,2917	218			BIM 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)
Order numbe Sample descri Administrator Test instrume Serial number Test condition	er Iption r	9039784000 6.2; Outer		112001		Referat Metallographie und Elektronenmikroskopie				
Sample descri Administrator Test instrume Serial number Test condition	iption r	6.2; Outer								
Administrato Test instrume Serial number Test condition	r.	Sample description 6.2; Outer			- Aller		Duran and			
Test instrume Serial number Test condition		Silcher								
Serial number	Test instrument Zwick Z 32									
Serial number										
Test condition	Serial number H2932-002									
i cat contaition	15									
⊡ HV 1	0	DIN EN ISO	6507-1.201	8-07						
HDVV		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		Reference	227 111/ 40			
plate	μm	μm	mm	HV		Neierence.	237 HV 10			
Indentation	fentation d ₁		d ₁ d ₂		dm	Hardness	Mean value	Distance in	Remark	
10.	μm	μm	mm	HV	HV	mm	Nemark			
1	279,0	280,4	0,2797	237	233					
2	281,2	283,5	0,2824	233						
3	280,0	280,4	0,2802	236			BM 1			
5	284.0	285.4	0,2843	229						
1	252.8	255.5	0.2542	223						
2	241.2	244.1	0.2426	315			ΗΔ7 1			
3	252.2	256.4	0.2543	287	267					
4	275.4	276.7	0.2761	243	17134		11/ \21			
5	305.5	302.0	0.3038	201						
1	313,8	312,2	0,3130	189						
2	320,9	319,2	0,3201	181						
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	269,0	269,4	0,2692	256						
2	295,1	252,2	0,2736	248						
3	254,7	253,6	0,2542	287	245					
4	294,5	290,0	0,2923	217						
5	292,2	292,5	0,2923	217						
	285.6	286.0	0,2855	228						
2	282.1	285.4	0.2837	227	229		BM 2			
4	278.6	278.3	0.2784	239	220					
5	289.8	287.5	0,2886	223						
			-1							
Date: 0 Tester: S)6.11.22 Scheck									



\sim				Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000	i i					
Sample desc	ription	6.2; Root						
Administrato	or	Silcher						
		7	(mar)					
Test instrum	ent	ZWICK Z 323	(neu)					
Serial numbe	er	H2932-002-	50430					
Test conditio	ns							
D HV	10	DIN EN ISO	6507-1.201	8-07		_		
	10	DIN EN ISO	0007-1.201					
L HBW		DIN EN ISO	6506-1:201	5-02				
HRC		DIN EN ISO	6508-1:201	6-12				
	Test ten	nperatur, if ou	utside (23+	45) °C				
Control	280.6	280.8	0.281	235		1222	Interneta.	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d,	d	Hardness	Mean value	Distance in		
no.	μm	μm	mm	HV	HV	mm	Kemark	
1	280,8	284,1	0,2825	232	223			
2	287,7	288,7	0,2882	223				
3	284,2	292,0	0,2881	223			BM 1	
4	288,7	291,6	0,2902	220		1		
5	291,0	293,1	0,2925	217				
2	207,3	207,5	0,2073	216				
3	300.6	299.7	0,2002	206	212		HA7 1	
4	297,9	298.5	0,2982	209				
5	303,7	302,4	0,3030	202				
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		VVIVI	
4	311,3	309,1	0,3102	193				
5	210.7	310,1	0,3106	192			é	
2	305.1	305.5	0 3053	192				
3	309.9	309.3	0.3096	193	192		HAZ 2	
4	312.6	311.3	0,3120	191	Academ			
5	314,5	316,1	0,3153	187				
1	292,1	296,6	0,2943	214				
2	291,2	292,2	0,2917	218			DMA	
3	291,0	292,7	0,2918	218	217		BIM 2	
4	290,6	295,6	0,2931	216				
5	200,5	292,1	0,2900	220				
Date: Tester:	06.11.22 Scheck							

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

3.19 P460 NH

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

The relevant material-specific data is as follows:

Table 3.58: Characteristics P460 NH

Production year	2017			
Production standard	DIN EN 10028-3			
Specific minimum characteristics	R _e [MPa]	445		
	R _m [MPa]	570		
	K _v [J]	40		
Material characteristics	R _e [MPa]	488		
	R _m [MPa]	652		
	K _v ¹⁴ [J]	80		

Table 3.59: Chemical composition of P460 NH

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
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_{Jlc} [MPa \sqrt{m}]
P460 NH	Base material	8	104.1
P460 NH	Weld material	8	154.9

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

- 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}	STUTTGA		MP	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample descr	iption	8.1; Outer	ayer					
Administrato	or	Silcher						
T		7. inter 7 202	(nou)		and the second			
lest instrum	Secial number H2022.00							
Serial number H2932-002			50430					
Test conditio	ns							
I HV	10	DIN EN ISO	6507-1:201	8-07		A constant	A MARKET AND A MARKET	
			6506 1:201	5.02		CHU -		
		DIN EN ISO	0500-1.201	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		Reference:	237 HV 10	
plate	μm	μm	mm	HV		increased.	237 HV 10	
Indentation	d,	dz	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	2010/06/06/	
	200.0	202.6	0 2012	204				
2	301.0	302,6	0,3013	204	206			
3	302.2	307.8	0.3050	199			BM 1	
4	293,1	298,9	0,2960	212				
5	292,5	298,5	0,2955	212				
1	269,4	270,5	0,2699	254				
2	269,2	270,1	0,2696	255				
3	270,2	268,8	0,2695	255	255		HAZ 1	
4	271,9	268,6	0,2703	254				
5	268,8	269,4	0,2691	256				
1	278,6	275,2	0,2769	242				
2	281,3	276,7	0,2790	238	242			
3	275,4	2/5,2	0,2753	245	242			
4	280.2	275,0	0,2759	244				
1	266.1	266.5	0,2763	255				
2	264.6	267.3	0,2000	262			1	
- 3	266.9	269.6	0.2683	258	261		HAZ 2	
4	263.6	269.4	0.2665	261	1000		1	
5	265,5	265,7	0,2656	263				
1	310,5	313,8	0,3122	190				
2	307,0	310,5	0,3088	195]	
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: Tester:	06.11.22 Scheck							
	recentering the							

Figure 3.77: Hardness measurements of P460 NH (1)

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample desc	ription	8.1; Center	f					
Administrate	or.	Silcher			and the second s			
Test instrum	ent	Zwick Z 323	(neu)	141				
Serial number	21	H2932-002-	50430			New Contract		
Test conditio	ins							
I HV	10	DIN EN ISO	6507-1:201	8-07			Marine I.	
HBW		DIN EN ISO	6506-1:201	5-02				
			6508-1-201	6-12				
	Test tem	peratur, if ou	tside (23+/-	5) °C				
Control	280.6	280.8	0.281	235		2202	heren waarde.	
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	d_m	Hardness	Mean value	Distance in	Provent	
no.	μm	μm	mm	HV	HV	mm	Kemark	
	200.0	200.4	0.0005	007				
1	299,9	299,1	0,2995	207	206			
2	299,3	300,2	0,2997	200				
3	296.6	302,4	0,3000	203			BM 1	
5	301.2	303.3	0.3022	203				
1	285.0	280.6	0.2828	232				
2	292.3	291.4	0.2918	218	1 1			
3	282,3	283,9	0,2831	231	233			
4	286,9	283,9	0,2854	228	a an		11742 1	
5	269,8	268,4	0,2691	256	1 1			
1	291,4	289,3	0,2904	220				
2	279,4	277,7	0,2786	239	1 [
3	288,7	284,2	0,2864	226	230		WM	
4	287,9	284,4	0,2861	227				
5	281,5	279,0	0,2802	236				
1	274,2	276,7	0,2754	244				
2	308,9	309,3	0,3091	194				
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	202	-	5.4.5	
3	302,0	305,9	0,3040	201	202		BM 2	
4	304.9	306.8	0,3042	198	1 1			
	504,5	500,0	0,0000	190				
Date: Tester:	06.11.22 Scheck							

Figure 3.78: Hardness measurements of P460 NH (2)

\mathbb{N}			MF	Test rep PAS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000	6			N. N. (1997)		
Sample desc	ription	8.1; Root			A REAL PROPERTY AND A REAL			
Administrato	or	Silchor						
-								
lest instrum	ent	Zwick Z 323	(neu)					
Serial numbe	er	H2932-002-	50430					
Test conditio	ins							
I HV	10		6507 1.201	9.07		A CONTRACT	Mar and a second	
	10		0307-1.201	0-07		ALC: NOT	No.NO. STREET	
L] 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	0,281 235				
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	Nemork	
	202.0	200.4	0.0005	014				
1	292,9	300,1	0,2965	211	205			
2	299,1	302,8	0,3010	203				
4	304 1	306.2	0.3051	199			BINI 1	
5	297.0	302.0	0 2995	207		-	1	
1	261.9	260.5	0.2612	272				
2	259.3	262.4	0,2608	273		2		
3	260.9	258.4	0.2597	275	276			
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	276,5	0,2781	240			1	
3	278,3	276,1	0,2772	241	242		I WM	
4	275,8	277,3	0,2766	242			1	
5	278,1	277,3	0,2777	240				
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	262,1	0,2609	272			4	
5	264,6	264,6	0,2646	265				
1	303,5	308,2	0,3058	198				
2	302,8	309,1	0,3060	198	100			
3	300,6	305,3	0,3029	202	198	-	BM 2	
4	305.9	310,7	0,3073	195			•	
5	505,8	510,5	0,5001	185				
Date: Tester:	06.11.22 Scheck	-						
and constraints in the	Learners d'he							

Figure 3.79: Hardness measurements of P460 NH (3)

\sim				Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numbe	er	9039784000						
Sample descr	iption	8.2; Outer	layer					
Administrato	r	Silcher						
		7.1.7.000	(
lest instrume	ent	ZWICK Z 323	(neu)					
Serial numbe	r	H2932-002-	50430					
Test conditio	ns							
			6507-1-201	8-07	and the second	- All and and		
			0507-1.201	5.00				
L] HBW		DIN EN ISO	6506-1:201	5-02				
HRC		DIN EN ISO	6508-1:201	6-12				
	Test ten	peratur, if ou	itside (23+/	-5) *C				
Control	280,6	280.8	0,281	235		D -1		
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	d_m	Hardness	Mean value	Distance in	Description	
no.	μm	μm	mm	HV	HV	mm	Kemark	
							-	
1	291,0	292,5	0,2917	218	218			
2	296,6	299,7	0,2982	209				
3	290,2	294,1	0,2921	217			BM 1	
4	287,1	291,2	0,2891	222				
5	260,0	269,3	0,2077	224				
2	203,4	269.6	0,2033	253				
3	274.0	271.9	0.2730	249	253			
4	277.9	267.1	0.2725	250				
5	266,7	271,3	0,2690	256				
1	279,2	277,3	0,2782	240				
2	282,7	277,1	0,2799	237	[
3	276,7	275,0	0,2758	244	242		. WM	
4	275,0	274,0	0,2745	246				
5	275,2	2/5,4	0,2753	245	-			
1	2/1,5	212,1	0,2721	250				
2	269,2	266.5	0,2078	259	256	<u></u>		
4	266 7	263.4	0.2651	264	200			
5	274.0	273.8	0,2739	247			1	
1	308,9	310,5	0,3097	193				
2	309,5	311,5	0,3105	192]	
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				
Date: (06.11.22 Scheck							

Figure 3.80: Hardness measurements of P460 NH (4)

			MF	Test rep AS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000						
Sample descr	iption	8.2; Root					Contraction of the	
Administrato	r	Silcher						
Loct Instrument Zwick 7.32			(2011)					
lest instrument ZWICK Z 32			(neu)					
Serial numbe	r	H2932-002-	50430					
Test conditio	ns							
J HV	10	DIN EN ISO	6507-1.201	8-07				
						STATE OF		
HBVV		DIN EN 150	0500-1.201	5-02				
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		Reference	227 414 40	
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	nemore	
	000.4	001.0	0.0005			0		
1	300,1	304,9	0,3025	203	204			
2	299,7	303,0	0,3014	204				
3	300,1	303,0	0,3016	204			DIVI I	
4	209.7	305,5	0,3045	200				
1	265.0	260.6	0,2935	207				
2	265.3	265,5	0,2654	263				
3	260.3	260.9	0,2606	273	269		HA7 1	
4	256.6	256.8	0.2567	281	200	<u>.</u>	11/ 12	
5	263.2	263.6	0 2634	267				
1	284.0	277.5	0.2807	235				
2	279.4	282.5	0,2809	235				
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	266,9	0,2644	265				
3	258,4	258,8	0,2586	277	266		HAZ 2	
4	267,8	266,1	0,2669	260	[
5	263,6	266,5	0,2651	264				
1	294,3	304,5	0,2994	207				
2	295,4	304,1	0,2997	206	007			
3	295,2	299,9	0,2975	209	207	-		
4	294,3	301,6	0,2980	209				
5	301,2	305,1	0,3031	202				
Date: Tester:	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	DIN 2470/2 / DIN 17172 / Ruhrgas Standard					
	RN 4205					
Specific minimum characteristics	R _e [MPa]	491				
	R _m [MPa]	598				
	K _v /A [kgm/cm ²]	4				
Material characteristics	R _e [MPa]	517				
	R _m [MPa]	648				
	K _v /A [kgm/cm ²] ¹⁵	7.1				

Table 3.62: Chemical composition of X70

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.12	0.25	1.56	0.02	0.009			
	Ni	V	Ti	Nb				
		0.05		0.049				

Table 3.63: Fracture toughness of X70

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

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

- 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:

Draduction year	2017	
Froduction year	2017	
Production standards	DIN EN ISO 3183	Annex M
Specific minimum characteristics ¹⁶	R _e [MPa]	485
	R _m [MPa]	605
	K _v [J]	90
Material characteristics	R _e [MPa]	527
	R _m [MPa]	627
	K _v ¹⁷ [J]	280

Table 3.64: Characteristics of L485

Table 3.65: Chemical composition of L485

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
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 _{Jlc} [MPa \sqrt{m}]
L485	Base material	2	134.2
L485	Weld material	2	129.8
L485	Heat-affected zone	2	92.4
L485	Base material	17	124.3
L485	Weld material	17	146.5
L485	Weld material of girth weld	17	100.8
L485	Base material (air)	32	480.4 ¹⁸
L485	Base material	33	203.2
	(0.2 bar)		
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}			MF	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order num	ber	9039784000	E	A.S.	ATTE	CALIFORNIA CONTRACTOR	TITLE	
Sample des	cription	17.1; Outer	layer		and a stand			
Administrat	or	Silcher				Charles and the second second second		
Tact instrum	aant	Turiale 7 222	(2011)					
lest instrun	nent	ZWICK Z 323	(neu)			Mar State		
Serial numb	er	H2932-002-	50430					
Test condition	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				
	Test temp	peratur, if out	tside (23+/-	5) °C				
Control	280.6	280.8	0.281	235			lane and the	
plate	μm	μm	mm	HV		Keterence:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Permark	
no.	μm	μm	mm	HV	HV	mm	Kennark	
1	287,1	289,1	0,2881	223	227			
2	283,1	288,9	0,2860	227				
3	285,2	287,1	0,2861	227			BINI 1	
4	202,7	280,0	0,2853	229		-		
1	202,3	207,7	0,2005	220				
2	288.5	290,0	0,2900	220				
3	290.6	293.3	0,2919	218	220			
4	291.4	290.4	0 2909	219	220			
5	284.4	291.2	0.2878	224				
1	285.8	279.8	0.2828	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	
1	286,6	286,4	0,2865	226				
2	284,4	289,5	0,2870	225				
3	280,2	284,8	0,2825	232	228		HAZ 2	
4	285,2	282,3	0,2837	230				
5	283,8	288,3	0,2860	227				
1	288,1	291,4	0,2898	221				
2	287,7	288,9	0,2883	223				
3	283,3	288,7	0,2860	227	227		BIM 2	
4	283,1	286,2	0,2847	229				
5	280,4	203,3	0,2819	233				
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}				Test rep PAS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order num	per	9039784000)		ARTIN			
Sample desc	ription	17.1; Roo	t					
Administrat	or	Silcher				To a statistical statis		
Test instrum	nent	Zwick Z 323	(neu)			Seal of the seal of the	A second second	
Serial numb	er	H2932-002-	50430					
Test condition	ons							
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 temp	eratur, if out	side (23+/-	5) °C				
Control	280.6	280.8	0.281	235		0284	lentropictus.	
plate	um	um	mm	HV		Reference:	237 HV 10	
Indentation	d.	d.	d	Hardness	Mean value	Distance in		
no.	μm	μm	mm	HV	HV	mm	Remark	
1	285,2	293,1	0,2891	222	220			
2	287,1	291,0	0,2890	222			BM 1	
3	287,1	292,7	0,2899	221				
4	209,5	294,5	0,2918	210				
1	286.0	288.3	0.2872	225	· · · · · · · · · · · · · · · · · · ·		11	
2	282.3	282.3	0.2823	233				
3	280,6	282,1	0,2814	234	231		HAZ 1	
4	280,2	278,3	0,2793	238	23-3-5210-C			
5	286,0	285,8	0,2859	227				
1	284,2	285,8	0,2850	228				
2	278,8	280,4	0,2796	237			10/10	
3	281,2	283,5	0,2824	233	229			
4	287,7	287,7	0,2877	224		-		
5	200,4	290,0	0,2882	223			й	
2	290,0	293,3	0,2950	213				
2	285.0	286.4	0 2857	227	230		HAZ 2	
4	279.8	275.0	0,2774	241				
5	274,8	278,1	0,2765	243				
1	286,4	285,8	0,2861	227				
2	285,0	289,3	0,2872	225			BM 2	
3	280,0	286,2	0,2831	231	229			
4	283,7	287,9	0,2858	227				
5	277,9	204,8	0,2813	234				
Date:	06.11.22			3				
Tester:	Scheck							

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

\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order num	ber	9039784000	ř.						
Sample des	ription	17.2; Outer	layer				A SALAR AND A SALAR AND A		
Administrat	or	Silcher							
Test instrum	ant	Tuick 7 222	(nou)			The Marken Street	A superior		
rest instrum	hent	ZWICK Z 323	(neu)						
Serial numb	er	H2932-002-	50430			1			
Test condition	ons					The second			
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 temp	eratur, if out	side (23+/-	5) °C					
Control	280.6	280.8	0,281	235		Deferre			
plate	μm	μm	mm	HV		Keterence:	237 HV 10		
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	Action		
	204.4	202.0	0.2901	222			-		
1	284,4	293,9	0,2891	222	223				
2	286.0	286.9	0,2864	224			BM 1		
4	286.2	289.8	0,2880	220			DIVIT		
5	289.1	291.8	0 2905	220					
1	292.0	291.0	0,2915	218					
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	14-14				
5	302,8	299.7	0,3013	204					
1	282,9	286,6	0,2848	229			-		
2	285,4	282,1	0,2837	230					
3	287,1	284,6	0,2858	227	229		WM		
4	285,6	281,7	0,2836	231					
5	285,4	285,6	0,2855	228					
1	294,6	290,4	0,2925	217					
2	288,3	282,7	0,2855	227					
3	281,7	282,3	0,2820	233	220		HAZ 2		
4	288,5	292,4	0,2905	220					
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		BIVI Z		
4	283,7	287,1	0,2854	228					
5	285,8	290,4	0,2881	223					
Date: Tester:	06.11.22 Scheck								

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

\sim	STUTTGART			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order num	ber	9039784000	1						
Sample desc	ription	17.2; Root					MAR Danne		
Administrat	or	Silcher							
Test instrum	ant	7. del: 7.222	(= =)			A Sheathart	6		
restinstrun	ient	ZWICK Z 323	(neu)						
Serial numb	er	H2932-002-	50430						
Test condition	ons				and the second	a starter and			
⊡ HV	10	DIN EN ISO	6507-1:201	8-07	And the setue of t	2.4			
□ 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			leterate at		
plate	μm	μm	mm	HV		Reference:	237 HV 10		
Indentation	d,	d ₂	d,,	Hardness	Mean value	Distance in	Demed		
no.	μm	μm	mm	HV	HV	mm	Kemark		
1	287,1	292,5	0,2898	221	220	2			
2	201,1	290,4	0,2890	222			BM 1		
3	288,7	293,3	0,2910	219			DIVI		
4	209,0	293,9	0,2910	210					
1	308.0	309.3	0,2090	195					
2	301.0	308.2	0,3046	200		-			
3	295.4	299.1	0.2972	210	204	-	HAZ 1		
4	300.8	299.9	0.3003	206					
5	295.4	296.4	0.2959	212					
1	314,7	293,5	0,3041	201					
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					
5	296,2	295,4	0,2958	212					
1	307,4	305,5	0,3065	197					
2	298,1	302,8	0,3004	205					
3	296,6	298,1	0,2974	210	210		TIAZ Z		
4	290,4	292,1	0,2912	219					
5	292,7	290,4	0,2915	218					
1	285,4	288,9	0,2872	225					
2	202,7	200,7	0,2847	229	220		BM 2		
3	200,0	290,8	0,2002	223	220				
	281.0	285.8	0.2834	230					
5	201,0	200,0	0,2004	201					
Date: Tester:	06.11.22 Scheck								

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

\mathbb{N}			Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	ber	9039784000	E.					
Sample desc	ription	40.1; Outer	layer					
Administrat	or	Silcher						
Test instrum	ant	7	6					
rest instrum	ient	ZWICK Z 323	(neu)					
Serial numb	er	H2932-002-	50430			2 days and		
Test condition	ons			in the second				
⊡ HV	10	DIN EN ISO	6507-1:201	8-07		Star and		
🗆 HBW		DIN EN ISO	6506-1:201	5-02				
HRC		DIN EN ISO	6508-1:201	6-12				
	Test temp	eratur, if out	side (23+/-	5) *C				
Control	280,6	280,8	0,281	235		Deferences		
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	Nemark	
	000 5	001.0	0.0001					
1	232,5	231,6	0,2321	344	351			
2	230,0	230,2	0,2301	350				
4	228,0	228.5	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		HAZ 1	
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			14/64	
3	230,2	232,9	0,2315	346	345		VVIVI	
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	3/3		HA7 2	
4	233.1	233.3	0.2332	341	545			
5	232.9	235.4	0,2341	338				
1	230.8	228.9	0.2299	351				
2	230,8	232,3	0,2315	346			1	
3	230,6	231,4	0,2310	347	346		BM 2	
4	231,6	231,0	0,2313	347				
5	233,3	233,5	0,2334	340				
Date:	06.11.22	I						
Tester:	Scheck							

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

\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order num	ber	9039784000	l.						
Sample desc	ription	40.1; Root	t.						
Administrat	or	Silcher							
Test instrum	nent	7wick 7 323	(neu)						
Corial numb		LI2022.002	(1104)			Serley Contenant Se			
Serial numb	er	H2932-002-:	50430						
Test conditio	ons					Page 1			
🖸 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 temp	eratur, if out	side (23+/-	5) °C					
Control	280.6	280.8	0.281	235		P 1			
plate	μm	μm	mm	HV		Reference:	237 HV 10		
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark		
no.	μm	μm	mm	HV	HV	mm	Action		
4	222.0	222.2	0.0006	242					
2	232,9	232,3	0,2320	343	350	 			
3	229.8	230,2	0,2303	350		1			
4	229.8	228.9	0.2294	352					
5	226,9	229,6	0.2282	356		1			
1	229,6	228,9	0,2293	353					
2	227,7	227,9	0,2278	357			1		
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		**************	*****************		
1	228,9	232,3	0,2306	349					
2	234,5	230,8	0,2327	343			10/04		
3	227,7	228,3	0,2280	357	366		VVIVI		
4	216,9	217,1	0,2170	394					
5	220,0	210,4	0,2192	360					
2	241,0	243,1	0,2423	352					
2	229,2	230,2	0.2286	355	345	-	HA7 2		
4	230.2	230.0	0.2301	350	040	<u>.</u>			
5	229.8	230.0	0.2299	351					
1	228.7	228.3	0,2285	355		1			
2	228,5	230,6	0,2296	352			1		
3	231,0	230,4	0,2307	348	350		BM 2		
4	230,0	230,8	0,2304	349					
5	231,6	230,8	0,2312	347			-		
Date:	06 11 00								
Tester:	Scheck								

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

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

The relevant material-specific data is as follows:

Table 3.67: Characteristics of L485

Production year	2009			
Production standard	DIN EN ISO 3183 Annex M			
Specific minimum characteristics	R _e [MPa]	485		
	R _m [MPa]	570		
	K _v [J]	58		
Material characteristics	R _e [MPa]	559		
	R _m [MPa]	656		
	K _v [J]	230		

Table 3.68: Chemical composition of L485

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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}	STUTTO		MF	Test rep PAS-PPB 523 Hardness	oort 10-08/1 test	Re Metallo Elektrone	graphie und enmikroskopie
Order numb	er	9039784000	0	12			
Sample desc	ription	2.1 Outer l	ayer	1999			
Administrate	or	Silcher					
Test		7	-words rand	1			
Test instrum	ent	Zwick Z 323	(neu)	the second			
Serial number	er	H2932-002-	50430				
Test conditio	ns			N.			
⊡ 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			
	Test tem	neratur if ou	teide (22+)	5)*0			
	200.0	200.0	0.004	1 225		1 URGH	filling an ann
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
Indented	/			Unrdener	Mannumburg	Distance in	
Indentation	a1	α ₂ μm	a _m	Hardness	HV HV	Distance in mm	Remark
	Paul						
1	285,0	283,1	0,2841	230		1	
2	282,1	285,8	0,2839	230	228		
3	281,2	287,1	0,2841	230		1	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			
2	299,9	299,9	0,2999	206	1000000		HAZ 1
3	297,2	297,6	0,2974	210	207	1	
4	295,6	298,3	0,2969	210			
5	293,7	297,2	0,2955	212		5	
1	293,1	298,1	0,2956	212			
2	292,9	297,9	0,2954	213	221948		10/11/1
3	292,0	293,9	0,2930	216	214		VVIVI
4	292,7	294,1	0,2934	215			
5	295,4	292,9	0,2941	214	12	1	
1	303,2	207.9	0,3041	201			
2	297.9	291,0	0,3002	211	208		HAZ 2
3	302.6	2027	0.2077	209	200		
5	298.7	294.7	0 2967	211			
1	275.2	287.3	0.2812	234			
2	273.4	283.9	0,2787	239			
3	273.4	286.9	0,2801	236	238		BM 2
4	271.5	283.8	0,2776	241	1.1.1	-	
5	272,3	284,8	0,2786	239			
2							
Date: Tester:	06.11.22 Scheck						

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

\mathbb{N}	STUTTG	\mathbb{N}	MF	Test rep PAS-PPB 523 Hardness	00rt 10-08/1 test	Re Metallog Elektrone	ferat graphie und nmikroskopie
Order num	ber	9039784000	D	16		and it	
Sample desc	ription	2.1 Center		1			
Administrat	or	Cilebor		1028			
Auministrat		Slicher		100			
Test instrum	nent	Zwick Z 323	3 (neu)	100	-	And and the second	
Serial numb	er	H2932-002-	50430				
Test conditio	ons			200.00			
J HV	10	DIN EN ISC	6507-1:201	8-07	1		
HBW		DIN EN ISC	6506-1:201	5-02	Jan Ser		
HRC			8508 4-204	6.12			
		DIN EN ISC	0000+1:201	0-12			
	Test tem	peratur, if ou	itside (23+/	-5) °C		1.5	
Control	280,6	280,8	0,281	235	Reference: 237 HV 1		
plate	μm	μm	mm	HV	Tura secur processor	Na respective as man or	
Indentation	d,	d ₂	d _m	Hardness	Mean value	Distance in	Remark
10.	μm	μm	mm	HV	HV	mm	
1	287.7	286.4	0.2871	225			
2	287.5	289.5	0.2885	223	226		
3	283,9	290.0	0.2870	225			BM 1
4	279,8	289,6	0,2847	229			
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	0,3023	203	10124-00		
5	305,3	302,2	0,3038	201			
1	299,9	301,4	0,3007	205			
2	290,8	293,1	0,2919	218			\\/\/
3	294,3	292,7	0,2935	215	213		VVIVI
4	295,8	292,7	0,2942	214			
5	291,6	295,6	0,2936	215			
1	295,8	294,5	0,2952	213			
2	298,7	295,6	0,2971	210		1	HA7 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	293,9	0,2884	223			
2	200,1	297,0	0,2920	21/	220		BM 2
3	200,0	291,2	0,2915	218	220	5	2111 2
4	283.1	204.0	0,2090	222			
	203,1	234,1	0,2003	222			
	in the second	-					

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

Order number Sample descriptio Administrator Test instrument Serial number Test conditions HV 10 HBW HRC HRC HRC HRC 1 280 plate µr Indentation no. µr 1 27 2 260 3 260 4 260 5 260 1 280 5 290 1 280	90397840 n 2.1 Roo Silcher Zwick Z 3 H2932-00 DIN EN IS DIN EN IS DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ m	000 ot 123 (neu) 02-50430 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
Sample descriptio Administrator Test instrument Serial number Test conditions HV 10 HBW HRC HRC Control 280 plate µr Indentation d no. µr 1 27 2 26 3 260 4 260 5 260 1 288 2 288 3 29 4 290 5 290 1 280	n 2.1 Roo Silcher Zwick Z 3 H2932-00 DIN EN IS DIN EN IS DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	ot 23 (neu) 2-50430 SO 6507-1:201 SO 6508-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) *C 235 HV Hardness		Reference:	237 HV 10
Administrator Test instrument Serial number Test conditions HV 10 HBW HRC HRC HRC 1 Control 281 plate µ1 Indentation d no. µ1 22 261 3 261 4 261 5 261 1 281 2 281 3 29 4 291 5 291 1 281	Silcher Zwick Z 3 H2932-00 DIN EN 13 DIN EN 13 DIN EN 13 temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	23 (neu) 02-50430 SO 6507-1:201 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 46-12 4-5) *C 235 HV Hardness		Reference:	237 HV 10
Test instrument Serial number Test conditions HV 10 HBW HRC HRC HRC Test Control 289 plate µ Indentation no. µ 1 27 2 26 3 26 4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28	Zwick Z 3 H2932-00 DIN EN IS DIN EN IS DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	23 (neu) 02-50430 SO 6507-1:201 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
Serial number Test conditions HV 10 HV 10 HBW HRC Test Control 28 plate µi Indentation d no. µi 1 27 2 26 3 26 4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28	Zwick 2 3 H2932-00 DIN EN IS DIN EN IS DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	23 (neu) 02-50430 SO 6507-1:201 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
Serial number Test conditions HV 10 HBW HRC Test Control 281 plate µ1 Indentation d no. µ1 226 3260 4260 5260 1288 2326 3260 4260 5260 1288 2426 3260 1288 29 429 529 1288 329 429 529 1288	H2932-00 DIN EN IS DIN EN IS DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	02-50430 SO 6507-1:201 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
Test conditions HV 10 HBW HRC Test Control 280 plate µ1 Indentation no. µ1 1 27 2 261 3 261 4 263 5 266 1 283 2 288 3 29 4 299 5 299 1 280	DIN EN IS DIN EN IS DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	SO 6507-1:201 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
HV 10 HBW HRC HRC Test Control plate µI Indentation no. µI 1 27 2 26 3 268 4 268 1 27 2 266 3 268 4 268 3 268 3 268 3 268 3 268 3 268 3 268 3 268 3 268 3 268 3 268 3 268 3 299 4 299 5 299 1 288	DIN EN 13 DIN EN 13 DIN EN 13 DIN EN 13 temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	SO 6507-1:201 SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	18-07 15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
HBW HRC Test Control 280 plate µ Indentation d no. µ 1 27 2 263 3 266 4 268 1 27 2 266 3 268 4 268 3 268 4 268 3 269 4 298 3 29 4 299 5 299 1 280 3 29 4 299 5 299 1 280	DIN EN 13 DIN EN 13 temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	SO 6506-1:201 SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	15-02 16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
HRC Control 28i plate μi Indentation d no. μi 1 27 2 26i 3 26i 4 26i 5 26i 1 27 2 26i 3 26i 4 26i 5 26i 1 28i 3 29i 4 29i 5 29i 1 28i	DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
HRC Test Control 28i plate µi Indentation d no. µi 1 27 2 26i 3 26i 1 27 2 26i 3 26i 1 28i 2 28i 3 26i 1 28i 2 28i 3 29i 4 29i 5 29i 1 28i 3 29i 4 29i 5 29i 1 28i	DIN EN IS temperatur, if 0,6 280,8 n µm 1 d ₂ n µm	SO 6508-1:201 outside (23+/ 0,281 mm d _m mm	16-12 4-5) °C 235 HV Hardness		Reference:	237 HV 10
Test Control plate Z8 plate µI Indentation no. µI 1 27 2 26 3 260 4 269 5 266 1 28 2 28 3 260 4 269 5 260 1 28 3 29 4 290 5 290 1 280	temperatur, if 0,6 280,8 μm 1 d ₂ n μm	outside (23+/ 0,281 mm d _m mm	-5) °C 235 HV Hardness		Reference:	237 HV 10
Control 28 plate µ Indentation no. µ 1 27 2 26 3 26 4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28 1 28 2 28 3 29 4 29 5 29 1 28	0,6 280,8 n μm 1 d ₂ n μm	0,281 mm d _m mm	235 HV Hardness		Reference:	237 HV 10
plate µ Indentation no. µ 1 27 2 26 3 26 3 26 3 26 1 28 2 28 3 29 4 29 5 29 1 28 1 28 2 28 3 29 4 29 5 29 1 28	m μm 1 d ₂ m μm	mm d _m mm	HV Hardness		increating a	237 11 10
Indentation no. // // // // // // // // // // // // //	1 d₂ m μm	d _m mm	Hardness	THE REPORT OF THE REPORT OF	OIL PRODUCTION STREET, STORE STORE STORE	
no. µ 1 27 2 26 3 26 4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28 1 28 2 28 3 29 4 29 5 29 1 28	n µm	mm	1.11.1	Mean value	Distance in	Remark
1 27 2 26 3 26 4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28	270.2		HV	HV	mm	
1 27 2 26 3 26 4 26 5 26 1 28 2 28 3 29 4 290 5 29 1 28		0.0714	250			
2 20 3 26 4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28 1 28 1 28 3 29 4 29 5 29 1 28	78 2770	0,2711	252	247		
4 26 5 26 1 28 2 28 3 29 4 29 5 29 1 28	217,9	0.2743	245			
5 26 1 28 2 28 3 29 4 29 5 29 1 28	281 7	0,2757	240		-	BM 1
1 28 2 28 3 29 4 29 5 29 1 28	9.4 283.7	0.2766	242	1 1		
2 28 3 29 4 29 5 29 1 28	3.7 289.5	0,2866	226			
3 29 4 29 5 29 1 28	293.1	0.2914	218	1 1		HAZ 1
4 29 5 29 1 28	1.0 293.9	0,2925	217	219		
5 29 1 28	0.6 291.8	0.2912	219	(1012)		
1 28	0.6 293,7	0,2922	217	1 1		
	0.0 281.5	0,2807	235		1	
2 28	7.5 284,6	0,2860	227	1 1		
3 28	5,2 286,2	0,2862	226	228		WM
4 28	5,8 283,3	0,2851	228	78.488	l l	
5 28	8,1 287,3	0,2877	224			
1 28	5,7 291,0	0,2888	222			
2 29	3,5 291,8	0,2927	217] [
3 29	1,5 291,0	0,2913	219	217		HAZ 2
4 29	5,4 294,5	0,2950	213		l I	
5 28	9,8 298,5	0,2941	214			
1 26	5,1 282,1	0,2736	248	l l		
2 26	4,0 273,4	0,2687	257			
3 26	2,6 274,4	0,2685	257	255		BM 2
4 26	2,4 275,4	0,2689	256	1 1		
5 26	1,9 274,4	0,2682	258			
			L		<u> </u>	

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

\mathbb{N}	Surrey		MF	Test rep AS-PPB 523 Hardness	oort 10-08/1 test	Re Metallo Elektrone	e ferat graphie und enmikroskopie	
Order numb	er	9039784000)		000 .			
Sample desc	ription	2.2 Outer la	ayer	1				
Administrate	or.	Silebor	and a second at	1		Contraction of the second		
		Guerrer	5801//51	1.1.1				
lest instrum	ent	Zwick Z 323	(neu)	1000				
Serial number	er	H2932-002-	50430	100		Contraction of		
Test conditio	ns						the second second	
⊡ HV ·	10	DIN EN ISO	6507-1:201	8-07			A. Carl	
HBW		DIN EN ISO	6506-1:201	5-02	1			
		DIN EN ICO	0500 4-004	0.10				
	-	DIN EN ISO	0008-1:201	0-12				
	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	TOTAL SPECIFIC PROPERTY OF	the management of many or a	-	
Indentation	d,	d2	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	10100000000	
	269 4	277.1	0.2727	240		-	-	
2	200,4	280.0	0.2728	249	246			
3	268.4	280.8	0.2746	245				
4	269.0	282.3	0.2756	244			DIVI	
5	270.0	285.4	0.2777	240			1	
1	294,0	292.0	0,2930	216		1		
2	294.1	297.8	0,2960	212			HAZ 1	
3	288,9	298,5	0,2937	215	214			
4	298.5	294,7	0,2966	211	1926640			
5	291,8	290,8	0,2913	219			1	
1	291,0	291,4	0,2912	219		í I		
2	293,7	294,5	0,2941	214				
3	289,5	290,2	0,2899	221	218		WM	
4	291,4	291,4	0,2914	218		0		
5	292,5	291,2	0,2918	218				
1	317,6	314,7	0,3161	186		1		
2	289,6	288,1	0,2888	222	np engr			
3	290,0	297,0	0,2935	215	213	5	HAZ 2	
4	286,2	290,0	0,2881	223				
5	295,2	288,5	0,2919	218				
1	279,4	291,6	0,2855	227		U		
2	278,8	289,3	0,2840	230	220			
3	270,1	200,3	0.2022	233	230	-		
4	282.3	200,5	0.2864	202			1	
5	202,0	200,0	0,2004	220).		
Date:	06.11.22 Scheck		4					
Date: Tester:	06.11.22 Scheck	1				1		

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

\mathbb{N}	STUTIO		М	Test rep PAS-PPB 523 Hardness	00000000000000000000000000000000000000	Re Metallo Elektrone	e ferat ographie und enmikroskopie	
Order numb	er	9039784000)	6	000 1			
Sample desc	ription	2.2 Center		100		LENG	A State of the second s	
Administrate	or	Silcher		5				
Testint				1	-		1	
lest instrum	ent	Zwick Z 323	(neu)	1.1		1. Paulo 100		
Serial number	er	H2932-002-	50430	203		- million		
Test conditio	ns			33				
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	Carl II		11	
	Test tem	neratur if ou	tside (22+)	-5) °C				
-	200.0	200.0	0.204	225		- 1986-19	Terration of the terration	
Control	280,6	200,0	0,201	235		Reference:	237 HV 10	
pince	- pin	pm d	nun d	nv u		Distance in		
Indentation	a1	- d ₂	a _m	Hardness		Distance in	Remark	
110.	hui	- pm		nv	TIV .	mm		
1	286.2	293.3	0 2898	221				
2	281.5	292.9	0 2872	225	226	P		
3	279.6	287,9	0.2837	230			BM 1	
4	279,4	290,4	0,2849	228				
5	280,6	291,2	0,2859	227			1	
1	296,6	291,8	0,2942	214				
2	291,4	292,0	0,2917	218			HAZ 1	
3	292,2	292,9	0,2926	217	211			
4	299,3	297,2	0,2983	208		1		
5	304,5	307,6	0,3060	198				
1	291,4	290,6	0,2910	219				
2	291,6	288,3	0,2900	221	2070.00			
3	295,8	297,2	0,2965	211	215		VVIM	
4	294,1	285,4	0,2898	221				
5	302,6	302,0	0,3023	203				
1	292,0	292,9	0,2925	217				
2	294,3	292,9	0,2930	215	214			
0	290,0	290,0	0,2930	215	214			
4	298.1	299.1	0 2986	208			1	
1	280.4	288.5	0 2845	229				
2	279.2	282.9	0,2810	235			1	
3	283.5	290.2	0 2868	225	230		BM 2	
4	279.0	288.7	0,2838	230				
5	280,2	288,7	0,2845	229				
Date: Tester:	06.11.22 Scheck							

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

\mathbb{N}	STUTTG		м	Test rep PAS-PPB 523 Hardness	00000000000000000000000000000000000000	Re Metalio Elektrone	ferat graphie und nmikroskopie
Order numb	er	9039784000)	100	000		_
Sample desc	ription	2.2 Root		23	and the second second	E MENSE	all and a set of
Administrate	or	Silcher		1.00			
Test in stars				100			
lest instrum	ent	Zwick Z 323	(neu)	100			
Serial number	er	H2932-002-	50430	1000		- and -	
Test conditio	ns						
U HV	10	DIN EN ISO	6507-1:201	8-07	+		-
HBW		DIN EN ISO	6506-1:201	5-02	1	and and a	
HRC		DIN EN ISO	6508.1.201	6.12	100 m		
	Test tom	peratur if ou	tride (22+1	5) *C			
	and a	and a	LSIUE (23+A	-5) 0		1 (data -	The Court of the Court
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	µm d	mm	PIV .		Distance in	
Indentation	a,	a ₂	a _m	Hardness	Mean value	Distance in	Remark
110.	huu	pan -					
1	262,6	274,4	0,2685	257	-		
2	258,0	276,5	0,2672	260	256		
3	261,3	275,2	0,2683	258			BM 1
4	262,2	276,3	0,2692	256	Constant in the		
5	267,3	280,8	0,2741	247			
1	287,7	289,1	0,2884	223			1
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			
5	294,7	294,3	0,2945	214]	
1	289,8	291,2	0,2905	220			
2	288,7	287,7	0,2882	223			10/04
3	292,7	287,9	0,2903	220	222		VVIVI
4	286,2	287,1	0,2866	220			
D	291,2	290,0	0,2906	220			
2	209,3	200,0	0,2001	225			
4	291,0	200,3	0.2875	221	222		ΗΔ7 2
4	285.8	285.8	0.2858	227	~~~		
5	294.7	294.5	0.2946	214			
1	269.6	281.7	0.2756	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 CONDUCTION OF		22
5	269,4	280,2	0,2748	246			
Date: Tester:	06.11.22 Scheck						

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

3.22 L485 ME

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

The relevant material-specific data is as follows:

Table 3.69: Characteristics of L485 ME

Production year	2017	
Production standards	ISO 3183	
Specific minimum characteristics ¹⁹	R _e [MPa]	485
	R _m [MPa]	570
	K _v [J]	48
Material characteristics	R _e [MPa]	520
	R _m [MPa]	621
	K _v ²⁰ [J]	183

Table 3.70: Chemical composition of L485 ME

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	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 3183,	, Annex M
Specific minimum characteristics	R _e [MPa]	485
	R _m [MPa]	605
	K _v [J]	90
Material characteristics	R _e [MPa]	521
	R _m [MPa]	632
	K _v ²¹ [J]	264

Table 3.73: Chemical composition of L485 (batch 2)

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

			MF	Test rep AS-PPB 523 Hardness	10-08/1 test	Referat Metallographie und Elektronenmikroskopie				
Order num	ber	9039784000	ſ.	/						
Sample description		47.1 Outer								
Administrator		Silcher		1						
Test instrument		7wick 7 323	(neu)							
rest instrument			(1100)							
Serial number		H2932-002-50430								
Test condition	ons									
U HV	10	DIN EN ISO	6507-1:201	8-07						
🗆 HBW		DIN EN ISO	DIN EN ISO 6506-1:2015-02							
		DIN EN ISO 6508-1:2016-12								
	Test temp	peratur, if ou	tside (23+/-	5) °C						
Control	280,6	280,8	0,281	235	-	References				
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	Action			
		0.07.4	0.0005							
1	313,8	327,1	0,3205	181		_	BM 1			
	3093	327,3	0,3205	101	186					
4	297.6	314.0	0,3058	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			WM			
2	291,2	289,8	0,2905	220						
3	294,3	290,8	0,2926	217	218					
4	294,5	292,9	0,2937	215						
1	295,5	209,3	0,2914	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						
2	314,3	326,7	0,3205	181	181		BM 2			
3	311,6	326,3	0,3189	182						
4	312,6	324,0	0,3183	183						
5	315,1	329,0	0,3220	179						
Date: Tester:	06.11.22 Scheck									

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

			MF	Test rep PAS-PPB 523 Hardness	00000000000000000000000000000000000000	Referat Metallographie und Elektronenmikroskopie			
Order number 903978400			Î						
Sample description		47.1 Center	1						
Administrator		Silcher		1					
Test instrument		7wick 7 323	(neu)				and the second		
Contraction					A STREET	New Market Party	Second Second		
Serial number		H2932-002-	50430			Same of the			
Test condition	ons						N. Constant State		
⊡ HV	10	DIN EN ISO	6507-1:201	8-07					
HBW DIN EN ISO 6506-1:2015-02									
HRC		DIN EN ISO 6508-1:2016-12							
	Test temp	peratur, if out	tside (23+/-	5) *C					
Control	280,6	280,8	0,281	235		Pafaranca	00710/40		
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	306.2	210.2	0 3127	100					
2	312.6	324.0	0,3127	190		_	BM 1		
3	310.7	320.7	0.3157	186	185				
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	210		1		
3	295,8	296,8	0,2963	211			HAZ 1		
4	298,5	297,4	0,2980	209					
5	295,2	290,6	0,2929	216					
1	290,4	290,6	0,2905	220	220		WM		
2	290,6	291,8	0,2912	219					
3	290,4	292,0	0,2912	219					
4	289,3	286,0	0,2877	224					
5	290,6	289,5	0,2901	220			<u>.</u>		
1	298,3	302,2	0,3002	206	209				
2	298,9	299,3	0,2991	207					
3	294,5	297,0	0,2958	212					
4	294,7	297,6	0,2962	211					
5	290,0	299,3	0,2980	209					
1	306.9	324,0	0,3182	103	188		BM 2		
2	307.6	318.2	0 3130	180					
3	308.0	318.8	0.3134	189					
	306.4	317.6	0.3120	191		-			
		1							
Date: Tester:	06.11.22 Scheck								

Figure 3.102: Hardness measurements of L485, item no. 47 (2)
\mathbb{N}				Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Order num	ber	9039784000						
Sample desc	ription	47.1 Root		(/ States	
Administrat	or	Silcher						
Test instrum	nent	Zwick Z 323	(neu)	1				
Corial numb		L10022 002 1	50420			No set and		
Serial numb	er	H2932-002-3	50430	1				
Test condition	ons							
U HV	10	DIN EN ISO	6507-1:201	8-07				
HBW		DIN EN ISO	6506-1:201	5-02				
		DIN FN ISO	6508-1:201	6-12	and the second second			
	Test temp	eratur, if out	side (23+/-	5) *C				
Control	280,6	280.8	0,281	235		Deferrer		
plate	μm	μm	mm	HV		Reference:	237 HV 10	
Indentation	d,	d ₂	dm	Hardness	Mean value	Distance in	Remark	
no.	μm	μm	mm	HV	HV	mm	ACHIOIK	
	044.0	040.0	0.0454	407				
1	311,3	318,8	0,3151	187		_		
2	308.4	316.7	0,3127	190	189			
4	305.9	318.0	0.3120	191	100			
5	307.0	318.0	0.3125	190				
1	295,6	292,2	0,2939	215				
2	301,4	306,0	0,3037	201				
3	298,5	301,6	0,3000	206	208		HAZ 1	
4	293,3	299,5	0,2964	211				
5	299,9	302,4	0,3012	204			-	
1	291,8	294,1	0,2930	216				
2	295,2	291,8	0,2935	215	047		10/64	
3	292,2	290,4	0,2913	219	217			
4	290,4	292,0	0,2912	219				
1	295.6	298.9	0.2972	210	i i	-		
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				
5	297,7	303,7	0,3007	205				
1	313,6	324,6	0,3191	182				
2	310,9	324,8	0,3179	184				
3	313,4	324,4	0,3189	182	182		BIVI 2	
4	313,4	324,8	0,3191	182				
5	515,4	520,5	0,3190	101				
Date:	06.11.22				<u>I</u>			
Tester:	Scheck							

Figure 3.103: Har	dness measurements	of L485, item no.	47 (3)
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\mathbb{N}			MP	Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order num	ber	9039784000	ř.	61 ×		XX		
Sample des	ription	47.2 Outer	layer	11		Contra Sant		
Administrat	or	Silcher					1	
Test instrun	nent	7wick 7 323	(neu)			Sec. Sec.		
Social numb	or	L10022.002	(neu) 50420					
- I I'I'	CI	H2932-002-	50450					
Test condition	ons							
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	18 M 19 19 19 19 19 19 19 19 19 19 19 19 19			
	Test temp	peratur, if ou	tside (23+/-	5) °C				
Control	280,6	280,8	0,281	235		Deferences		
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	Remore	
4	207.9	215.2	0.2116	101				
2	308.2	316.3	0.3173	191				
3	308.6	318.6	0.3136	189	187			
4	312,0	319,9	0,3159	186				
5	314,9	325,3	0,3201	181				
1	548,9	311,9	0,4304	100				
2	293,5	297,3	0,2954	213			HAZ 1	
3	302,8	303,9	0,3034	202	188			
4	294,1	299,7	0,2969	210				
5	294,1	294,3	0,2942	214				
	290,0	291,0	0,2912	219			2	
3	289.8	286.6	0,2910	223	219		\\/\/	
4	290.2	292.9	0,2002	218	210			
5	291,6	291,8	0,2917	218				
1	302,0	307,5	0,3047	200				
2	298,3	304,1	0,3012	204				
3	295,4	299,7	0,2975	209	206		HAZ 2	
4	296,2	298,9	0,2975	209				
5	297,6	298,3	0,2980	209				
1	310,9	322,0	0,3198	181		-		
2	309.3	318.6	0.3139	188	186		BM 0	
4	308.4	316.3	0.3124	190				
5	308,9	319,0	0,3139	188				
Date:	06.11.22 Scheck							
.coult	Selleen							

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

\mathbb{N}				Test rep AS-PPB 523 Hardness	00rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie	
Order numb	ber	9039784000				XXX	
Sample desc	ription	47.2 Cente	r	11 and			
Administrat	or	Silcher					A
Tost instrum	ant	Twick 7 222	(0011)				
lest instrun	ient	ZWICK Z 323	(neu)			North Star	
Serial numb	er	H2932-002-	50430				
Test condition	ons						
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	All the second		
	Test temp	peratur, if out	side (23+4	5) °C			
Control	280.6	280.8	0.281	235		100	later Marke
plate	um	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d,	d	Hardness	Mean value	Distance in	-
no.	μm	μm	mm	HV	HV	mm	Kemark
1	297,0	296,4	0,2967	211			
2	304,1	315,9	0,3100	193	105		
3	302,0	317,2	0,3096	193	195		BM 1
	308,0	319.0	0,3133	188			
1	308.9	323.8	0,3163	185		***************	
2	297.2	293.9	0,2956	212			
3	295,8	296.2	0.2960	212	204		
4	297,4	297,0	0,2972	210			
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	296,0	0,2947	213		l	
5	293,9	290,4	0,2921	217		-	-
2	290,7	297,4	0,2901	209			
	295.4	297.8	0,2955	207	210		
4	304.7	303.0	0.3039	201			
5	290,0	290,2	0,2901	220			
1	315,5	326,3	0,3209	180			
2	312,8	320,1	0,3164	185			
3	309,7	315,9	0,3128	190	189		BM 2
4	311,1	310,7	0,3109	192			
5	309,9	305,0	0,3075	196			
Date: Tester:	06.11.22 Scheck						

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

\mathbb{N}			MF	Test rep AS-PPB 523 Hardness	10-08/1 test	Referat Metallographie und Elektronenmikroskopie	
Order num	ber	9039784000	ſ.	ar an	1.0	XX	
Sample des	cription	47.2 Root					
Administrat	or	Silcher					1
Test instrun	nent	Zwick Z 323	(neu)				1
Serial numb	er	L2032 002	225 (Hed)				
Test conditi		112932-002-	50450		1		
Test condition	ons						
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 temp	peratur, if ou	tside (23+/-	5) °C			
Control	280,6	280,8	0,281	235		Rafarance	227 111/ 40
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	2010/02/2020
1	212.2	220.5	0 3163	195			
2	309.7	320,5	0,3152	187		_	
3	309.1	320,9	0.3150	187	187		BM 1
4	307,6	320,3	0,3139	188			
5	308,2	318,4	0,3133	189			
1	296,2	301,4	0,2988	208			
2	299,1	303,5	0,3013	204			HAZ 1
3	301,0	302,0	0,3015	204	204		
4	303,3	304,9	0,3041	201			
5	299,9	300,3	0,3001	206	-		
1	292,9	291,6	0,2923	217			
2	290,4	292,2	0,2913	219	217	-	
3	291,0	292,5	0,2920	217	217		
5	293.1	294.5	0.2938	215			
1	302,8	299,7	0,3013	204		- 2	
2	297,4	298,9	0,2982	209			
3	300,1	300,1	0,3001	206	206		HAZ 2
4	298,7	300,5	0,2996	207			
5	299,1	301,6	0,3003	206			
1	304,9	313,8	0,3094	194			
2	307.0	321 7	0,3144	188	190		BM 2
4	310.1	318.6	0.3144	188	130		
5	308,4	317,8	0,3131	189			
Date: Tester:	06.11.22 Scheck						

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

3.24 GRS550/X80

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

The relevant material-specific data is as follows:

Table 3.75: Characteristics of GRS550/X80

Production year	1992				
Production standard	DIN 17172 / API S	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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.1	0.4	1.97	0.016	0.001	0.03	0.05	0.01
	Ni	V	Ti	Nb				
	0.03		0.017	0.044				

Table 3.77: Fracture toughness of GRS550/X80

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

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

Samples were taken from the following areas:

- base material
- weld material of longitudinal weld

 $^{^{22}}$ Notched-bar impact test with V-notch at 0 $^{\circ}\mathrm{C}$



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}		RT	MP	Test rep AS-PPB 5231 Hardness	ort 10-08/1 test	Re Metallo Elektrone	e ferat ographie und enmikroskopie
Order numb	er	9039784000)		-	-	magen
Sample desc	ription	5.1; Outer l					
Administrator Silcher							
Test instrum	ant	Zwick Z 323	(neu)		A		
rest instrum	lent	L10022.002	50420				
Serial numbe	er	H2932-002-	50450	1000			
Test conditio	ons				i de st		
U HV	10	DIN EN ISO	6507-1:201	8-07			Martine .
HBW		DIN EN ISO	6506-1:201	5-02		S V Spel	1 mar
			6508-1-201	6-12		1224	
	-	DIN EN ISU	0000-1.201	512			
	Test temp	eratur, if ou	tside (23+/-	-5) °C			
Control	280,6	280,8	0,281	235		Reference:	237 HV 10
plate	μm	μm	mm	HV	Total concernance		
Indentation	d,	dz	d _m	Hardness	Mean value	Distance in	Remark
no,	μm	μm	mm	HV	HV	mm	104300000000
1	292.0	300.6	0 2963	211			
2	289.3	302.8	0,2961	212	213		
3	283,9	296,2	0,2901	220			
4	290,6	299,7	0,2952	213			BINI
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			1
3	293,1	291,2	0,2921	217	217		HAZ 1
4	286,4	295,6	0,2910	219			4
5	289,5	294,9	0,2922	217			
2	200,0	211,1	0,2709	230			1
2	279.6	277.5	0.2785	232	238		
4	274.4	273.8	0.2741	247	200		
5	283,3	281.5	0,2824	233			1
1	286,6	293,5	0,2901	220			
2	286,0	292,5	0,2893	222]
3	292,1	288,9	0,2905	220	220		HAZ 2
4	292,5	288,3	0,2904	220	[1
5	289,1	294,3	0,2917	218			
1	296,6	306,8	0,3017	204			1
2	298,5	300,2	0,3023	203	207		BM 2
3	290,4	303,2	0,2900	208	201		
5	293.3	303.0	0,2982	209			1
			-,				
Date:	06.11.22						
Tester:	Scheck						

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

\mathbb{N}		RT	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie	
Order numb	ber	9039784000)		-		-
Sample desc	ription	5.1; Center					
Administrat	or	Silcher		1000			- P
Test instrum	nent	Zwick Z 323	(neu)	1000			1
Serial numb	er	H2932-002-	50430			A A AN	
Test conditio		112002 002	00100				
	7115			1.0			
U HV	10	DIN EN ISO	6507-1:201	8-07	all all all		1000
HBW		DIN EN ISO	6506-1:201	5-02		1 Star Chine	-
HRC		DIN EN ISO	6508-1:201	6-12	and the second		
	Test temp	eratur, if out	side (23+/-	5) *C			
Control	280,6	280,8	0,281	235		Reference	227 41/ 40
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	2010/00/2005
1	285.6	297.2	0 2914	218			
2	287,3	296,0	0,2916	218			
3	290,0	300,8	0,2954	213	214		
4	289,1	297,9	0,2935	215			BIVET
5	298,1	305,1	0,3016	204			
1	294,1	290,8	0,2925	217			
2	290,8	292,2	0,2915	218	0.17		HAZ 1
3	291,6	292,2	0,2919	218	217		
4	293,3	291,8	0,2920	217		1	
1	293,1	291,2	0,2921	235			
2	284.6	282.7	0,2836	230		· · · · · · · · · · · · · · · · · · ·	
3	284.6	284.4	0.2845	229	232		
4	282,3	279,4	0,2808	235			1
5	284,6	282,3	0,2834	231			
1	295,2	292,5	0,2938	215			
2	297,0	289,2	0,2931	216			
3	288,3	296,2	0,2923	217	218		HAZ 2
4	290,8	268,5	0,2897	221			1
1	301.8	308.8	0,2090	199			
2	295.8	305.7	0,3008	205			
3	294.5	304.1	0,2993	207	209		BM 2
4	290,0	298,5	0,2942	214			
5	286,8	295,8	0,2913	219	[
Date: Tester:	06.11.22 Scheck						

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

			MF	Test report MPAS-PPB 52310-08/1 Hardness test			Referat Metallographie und Elektronenmikroskopie		
Order numb	er	9039784000)		-		andiguna		
Sample desc	ription	5.1; Root		100			AC.		
Administrate	or	Silebor							
Auministrate		Sicher		100			for all the		
Test instrum	ent	Zwick Z 323	(neu)	1900					
Serial numbe	er	H2932-002-	50430	1000					
Test conditio	ns			1205					
	10	DIN EN ISO	6507 1-201	9.07	and the second		North Contract		
	10	DIN EN ISC	0007-1.201	0-07	63.03 M	A REAL PROPERTY	NAME -		
HBW		DIN EN ISO	6506-1:201	5-02	The second second	Buch State			
HRC		DIN EN ISO	6508-1:201	6-12	the second s				
	Test tem	peratur, if ou	tside (23+/	-5) °C					
Control	280.6	280.8	0.281	235		19980	Transmission .		
plate	100,0	100,0	mm	HV		Reference:	237 HV 10		
Indontation	d.	d	d	Hardener	Mean value	Distance in			
no.	um	102	mm	HV	HV	mm	Remark		
	Part								
1	292.2	300,1	0,2962	211	211				
2	291,6	300,1	0,2959	212					
3	292,7	299,7	0,2962	211			BM 1		
4	292,3	298,7	0,2955	212					
5	294,5	299,3	0,2969	210					
1	279,8	284,0	0,2819	233			5		
2	291,8	290,4	0,2911	219	222				
3	295,0	209,0	0,2924	217	222		HAZT		
4	290,2	283.3	0,2929	210					
1	285.2	277.3	0.2813	234		-	7		
2	278.4	278.1	0.2783	240			-		
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	276,7	270,9	0,2738	247					
2	274,8	275,2	0,2750	245					
3	278,5	284,8	0,2817	234	235				
4	286,2	288,7	0,2875	224					
0	200,0	200,2	0,2001	227					
2	295.2	302,4	0,2990	200					
4	288.7	302.6	0.2957	212	210		BM 2		
3	291.0	300.1	0.2956	212	1.0770676				
3	200.0	299.7	0,2943	214			-		
3 4 5	200,9	20011							

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

\mathbb{N}				Test rep PAS-PPB 523 Hardness	0 0rt 10-08/1 test	Referat Metallographie und Elektronenmikroskopie		
Order numb	ber	9039784000)	-				
Sample desc	ription	5.2; Outer I	ayer			1.1.1	Sec. 1	
Administrator Silcher					A BANK			
Test instaur		7.4.4.7.202	(marin)					
Test Instrum	ient	ZWICK Z 323	(neu)					
Serial numb	er	H2932-002-	50430					
Test conditio	ons				100			
U HV	10	DIN EN ISO	6507-1:201	8-07	Sec. 1			
- HBW		DIN EN ISO	6506-1:201	5-02	the second second			
		BILLENICO	0000 1.201	0.02	121	Company of the local division of the local d		
I HKC		DIN EN ISO	0508-1:201	0-12				
	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			20111110	
Indentation no.	d₁ µm	d ₂ µm	d _m mm	Hardness HV	Mean value HV	Distance in mm	Remark	
		005.4					-	
1	291,2	305,4	0,2983	208		1		
2	294,3	304,7	0,2995	207	207		BM 1	
4	292,2	303.5	0,2903	200	207			
5	297.6	306.2	0.3019	203				
1	296,8	298,9	0,2979	209		1-		
2	297,7	289,8	0,2937	215		4	1	
3	289,0	294,8	0,2919	218	216		HAZ 1	
4	290,0	290,8	0,2904	220				
5	290,2	292,0	0,2911	219				
1	280,6	282,7	0,2817	234			,	
2	283,5	282,9	0,2832	231	224		WM	
3	283,9	281,3	0,2820	232	234			
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		1		
3	288,5	292,2	0,2904	220	219		HAZ 2	
4	293,7	287,5	0,2906	220				
5	280,4	292,9	0,2867	226		1	-	
1	299,7	305,5	0,3026	202		1 1	4	
2	297,2	308,5	0,3029	202	207		BM 2	
3	292,9	302,8	0,2978	209	207			
4	289.6	299.3	0.2944	214		1.	1	
5	200,0	20010	STRO TT				-	
Date: Tester:	06.11.22 Scheck		•					

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

\sim			MP	Test rep AS-PPB 523 Hardness	fort 10-08/1 test	Re Metallo Elektrone	e ferat ographie und enmikroskopie
Order num	ber	9039784000	0	-			
Sample dese	ription	5.2; Center			1 A.		E al and
Administrat	or	Silcher					
lest instrun	nent	Zwick Z 323	(neu)				
Serial numb	er	H2932-002-	50430			S STATIAN ST	
Test condition	ons				1		
U HV	10	DIN EN ISO	6507-1:201	8-07			Retto
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	tside (23+/-	5) °C			
Control	280.6	280.8	0.281	235		2292	hardonice na
plate	μm	μm	mm	HV		Reference:	237 HV 10
Indentation	d,	d,	d	Hardness	Mean value	Distance in	
no.	μm	μm	mm	HV	HV	mm	Kemark
			· ·			1	
1	285,0	295,8	0,2904	220			
2	285,2	301,8	0,2935	215	20.000]
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		1	
3	284,4	284,6	0,2845	229	221		HAZ 1
4	292,7	295,8	0,2942	214			
5	293,1	292,7	0,2929	216		1	
1	280,8	280,2	0,2805	236			4
2	284,4	281,3	0,2828	232	224	-	
3	282,3	282,9	0,2826	232	234	-	
4	200,4	2/0,3	0,2794	230			4
5	203,3	2027	0,2010	230			-
2	280.5	200.8	0,2933	210			
2	286.4	291.6	0.2800	220	221		HA7 2
3	290.6	286.0	0,2050	223	261		
5	285.4	288.9	0.2872	225		5	1
1	295.2	307.6	0.3014	204			
2	296.6	304.3	0.3005	205			1
3	293.5	306.6	0.3000	206	207		BM 2
4	292,9	304,5	0,2987	208	199496		1
5	289,8	301,0	0,2954	213		-	
(d			
Date: Tester:	06.11.22 Scheck						

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

Order number 9039784000 Sample description 5.2; Root Administrator Slicher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions 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 Reference: 237 HV 10 Indenation no. μm μm mm HV Distance in mm Rem 1 293,1 302,0 0,2975 209	\mathbb{N}	STUTTG		MF	Test rep PAS-PPB 523 Hardness	oort 10-08/1 test	Metallo Elektrone	e ferat graphie und enmikroskopie
Sample description 5.2; Root Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions	Order numb	er	9039784000)	-			-
Administrator Silcher Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions Image: Control plate DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 Image: Control plate Z80,8 0,281 Z35 Plate DIN EN ISO 6508-1:2016-12 Image: Control plate Z80,8 0,281 Z35 Onionization no. Z80,1 Gag Gag Z37 Reference: Z37 HV 10 Indentation no. d1 d2 dm Hardness Mean value Distance in mm Rem 1 293,1 302,0 0,2994 207 209 BM 1 293,3 302,0 0,2997 209 BM 1 283,6 291,4 0,2894 207 209 BM 1 282,0 288,1 0,2796 237 227 HAZ 2 276,1 283,1 0,2796 237 227 HAZ 2 278,2 276,5 0,2778 240 245 11 <t< td=""><td>Sample descr</td><td>iption</td><td>5.2; Root</td><td></td><td></td><td>A C</td><td></td><td>6/</td></t<>	Sample descr	iption	5.2; Root			A C		6/
Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2015-02 HRC DIN EN ISO 6508-1:2015-02 Image: Control plate pm plate pm µm µm µm µm µm µm 1 283,1 3295,4 304,3 299,9 0.2975 209 209 1 283,1 3295,4 304,3 0,299,7 212 5 293,3 3295,4 304,3 1 283,1 1 283,1 1 283,1 1 283,1 1 283,1 1 283,1 1 283,1 1 283,1 1 282,9 2 276,1 283,1 0,2796 2 276,1 282	Administrato	or	Silcher		1000			
Test instrument Zwick Z 323 (neu) Serial number H2932-002-50430 Test conditions DIN EN ISO 6507-1:2018-07 HW 10 DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) *C Control Z880,6 280,8 0,281 235 Reference: 237 HV 10 Indentation d1 d2 d4 HV Distance in mm Rem 1 293,1 302,0 0.2975 209 209 BM 1 293,1 302,0 0.2994 207 0 BM 1 283,1 302,0 0.2975 209 209 BM 1 283,1 302,0 0.2976 210 1 A 1 283,1 0,2894 207 209 BM 1 282,3 288,6 29,14 0.2986 222 209 HAZ 1 282,3 288,6 0.2889 222				6411115				
Serial number H2932-002-50430 Test conditions IN Ex IN Indentation Indentation<	lest instrum	ent	Zwick Z 323	(neu)	12.3			
10 DIN EN ISO 6507-1:2018-07 HBW DIN EN ISO 6506-1:2015-02 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) *C Control plate μm μm HV Reference: 237 HV 10 Indentation d ₁ d ₂ d _m Hardness Mean value Distance in mm Rem 280,6 280,8 0,2994 207 209 BM BM 1 293,1 302,0 0,2975 209 209 BM 2 297,0 301,8 0,2994 207 209 BM 3 285,4 304,3 0,2996 212 209 BM 4 281,4 299,9 0,2857 212 212 428,3 288,1 0,2826 223 227 HAZ 3 285,6 291,4 0,2885 223 227 HAZ 428,3 282,2 245 4245 4245 4273,2 276,5 0,2778	Serial numbe	er	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 plate μm μm mm HV Distance in mm Reference: 237 HV 10 Indentation no. d ₁ d ₂ d _m Hardness Mean value Distance in mm Rem 1 293,1 302,0 0.2975 209 0 BM 2 297,0 301,8 0.2994 207 0 0 6 3 295,4 304,3 0.2997 209 0 BM 4 291,4 299,9 0.29277 209 0 BM 1 282,3 288,1 0.2885 223 227 HAZ 5 287,1 290,8 0.2889 222 0 HAZ 4 282,9 284,0 0.2778 240 0 0 3 276,5	Test conditio	ns			12	1		
HBW DIN EN ISO 6506-1:2015-02 DIN EN ISO 6508-1:2016-12 HRC DIN EN ISO 6508-1:2016-12 Test temperatur, if outside (23+/-5) °C Reference: 237 HV 10 Control plate μm μm mm HV Reference: 237 HV 10 Indentation no. d, μm d, μm d, μm d, μm d, mm d, HV Mean value HV Distance in mm Ref 1 293,1 302,0 0,2975 209	⊡ HV 1	10	DIN EN ISC	6507-1:201	8-07			CHARLES
$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	HBW		DIN EN ISC	6506-1:201	5-02			
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	HRC		DIN EN ISO	6508-1-201	6-12	No. Concerning	and the second second	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$		Test tors	paratur if cu	telda (22+)	5) 10			
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	-	and a	and a				1,15	1
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	Control	280,6	280,8	0,281	235		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 $	pinte	μm	µm d	mm d	riv	Manufactor	Distances in	
Image Image <th< td=""><td>ndentation</td><td>um</td><td>d2 1000</td><td>a_m</td><td>Hardness</td><td>HV HV</td><td>Distance in</td><td>Remark</td></th<>	ndentation	um	d2 1000	a _m	Hardness	HV HV	Distance in	Remark
1 293,1 302,0 0,2975 209		Part						
2 297,0 301,8 0,2994 207 3 295,4 304,3 0,2998 206 209 BM 4 291,4 299,9 0,2957 212 212 209 100 5 293,3 302,0 0,2977 209 100 1	1	293,1	302,0	0,2975	209	209		
3 295,4 304,3 0,2998 206 209 BM 4 291,4 299,9 0,2957 212 12 12 12 5 293,3 302,0 0,2977 209 12	2	297,0	301,8	0,2994	207			
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 4 283,7 292,2 0,2880 224 227 5 287,1 290,8 0,2894 231 227 2 279,2 276,5 0,2778 240 245 3 276,3 275,8 0,2761 243 245 WM 3 276,3 275,8 0,2761 243 245 WM 3 276,3 275,8 0,2768 240 245 WM 2 263,2 268,8 0,2660 262 245 44 244 HAZ 4 274,8 279,2 0,2770 242 244 44 44 274,8 279,2 0,2770 242 244 44 44 274,8 279,2	3	295,4	304,3	0,2998	206			BM 1
5 243,3 302,0 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 4 283,7 292,2 0,2880 224	4	291,4	299,9	0,2957	212			1
1 282,3 288,1 0,2852 228 2 276,1 283,1 0,2796 237 227 HAZ 3 285,6 291,4 0,2885 223 227 1 1 4 283,7 292,2 0,2880 224 224 1 1 1 1 1 290,8 0,2834 231 227 1 1 1 1 289,9 284,0 0,2834 231 245 1 1 1 1 289,9 284,0 0,2778 240 245 1 1 1 1 1 1 1 1 279,2 276,5 0,2776 243 245 1	5	293,3	302,0	0,2977	209			
2 270,1 285,1 0,2790 237 3 285,6 291,4 0,2885 223 227 Image: constraint of the second se	1	282,3	288,1	0,2852	228			HAZ 1
3 250,0 251,4 0,2800 223 227 10 10 10 4 283,7 292,2 0,2880 224	2	270,1	283,1	0,2796	23/	227		
5 287,1 290,8 0,2889 222 1 282,9 284,0 0,2834 231 2 279,2 276,5 0,2778 240 3 276,3 275,8 0,2761 243 245 4 270,2 270,9 0,2706 253 245 5 269,4 269,6 0,2695 255	3	283.7	201,4	0,2880	223	221		
1 282,9 284,0 0,2834 231 2 279,2 276,5 0,2778 240 3 276,3 275,8 0,2761 243 245 4 270,2 270,9 0,2706 253 245 5 269,4 269,6 0,2695 255 269 1 278,8 276,5 0,2778 240 245 2 263,2 268,8 0,2660 262 44 2 263,2 268,8 0,2770 242 244 44 4 274,8 279,2 0,2770 242 244 44 4 274,8 279,2 0,2770 242 244 44 4 274,8 279,2 0,2770 242 244 44 1 298,5 306,2 0,3023 203 203 208 BM 2 296,4 305,7 0,3011 205 208 208 44 4 288,3 299,9 0,2941 214 208	4	287.1	290.8	0,2000	224			ł
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3 276,3 275,8 0,2761 243 245 WM 4 270,2 270,9 0,2706 253 5 269,4 269,6 0,2695 255 1 278,8 276,9 0,2778 240 40 40 2 263,2 268,8 0,2660 262 262 424 244 4274,8 279,2 0,2770 242 244 4274,8 279,2 0,2770 242 244 424 4274,8 279,2 0,2770 242 244 424 4274,8 279,2 0,2770 242 244 424 428,3 306,2 0,3023 203 203 203 203 203 208 BM BM 3 294,3 303,9 0,2991 207 208 208 BM BM 4 288,3 299,9 0,2941 214 208 BM 10	2	279.2	276.5	0,2778	240			
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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 4 288,3 299,9 0,2941 214	4	274,8	279,2	0,2770	242			
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	5	20010	00010	C LOUT	200			
P-1 00.44.00	Deter			-				
Date: 06.11.22	Date:	16.11.22						

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

Chamiaal	С	Si	Mn	Р	S	Cu	Cr	Мо
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_{Jlc} [MPa \sqrt{m}]
L415	Base material	9	108.5
L415	Weld material	9	138.4

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

Samples were taken from the following areas:

- base material
- weld material of the longitudinal weld



Figure 3.114: Crack growth L415

3.26 P355 NL1

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

The relevant material-specific data is as follows:

Table 3.81: Characteristics of P355 NL1

Production year	2013			
Production standard	API Spec. 5L (2013) / EN 10216-3			
Specific minimum characteristics	R _e [MPa]	345		
	R _m [MPa]	490		
	K _v [J]	43		
Material characteristics	R _e [MPa]	365		
	R _m [MPa]	529		
	K _v ²³ [J]	224		

Table 3.82: Chemical composition of P355 NL1

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	0.15	0.2	1.3	0.1	0.002	0.14	0.12	0.04
	Ni	V	Ti	Nb				
		0.05	0.001	0.013				

Table 3.83: Fracture toughness of P355 NL1

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

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

 $^{^{\}rm 23}$ 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

Chamical composition	С	Si	Mn	Р	S	Cu	Cr	Мо
[%]	3.822				0.0038			
	Ni	V	Ti	Nb				

Table 3.86: Fracture toughness of GJS400

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

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

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



Figure 3.116: Crack growth GJS400

3.28 P460 QL1

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

The relevant material-specific data is as follows:

Table 3.87: Characteristics of P460 QL1

Production year	2019		
Production standard	EN 10028-6 (2017)	
Specific minimum characteristics	R _e [MPa]	460	
	R _m [MPa]	550	
	K _v [J]	27	
Material characteristics	R _e [MPa]	464	
	R _m [MPa]	562	
	K _v ²⁵ [J]	282	

Table 3.88: Chemical composition of P460 QL1

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
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

Chamical	С	Si	Mn	Р	S	Cu	Cr	Мо
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
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
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.

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8 List of Abbreviations

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

9 List of Symbols

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

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