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Understanding of Grade 91 DMW Failures

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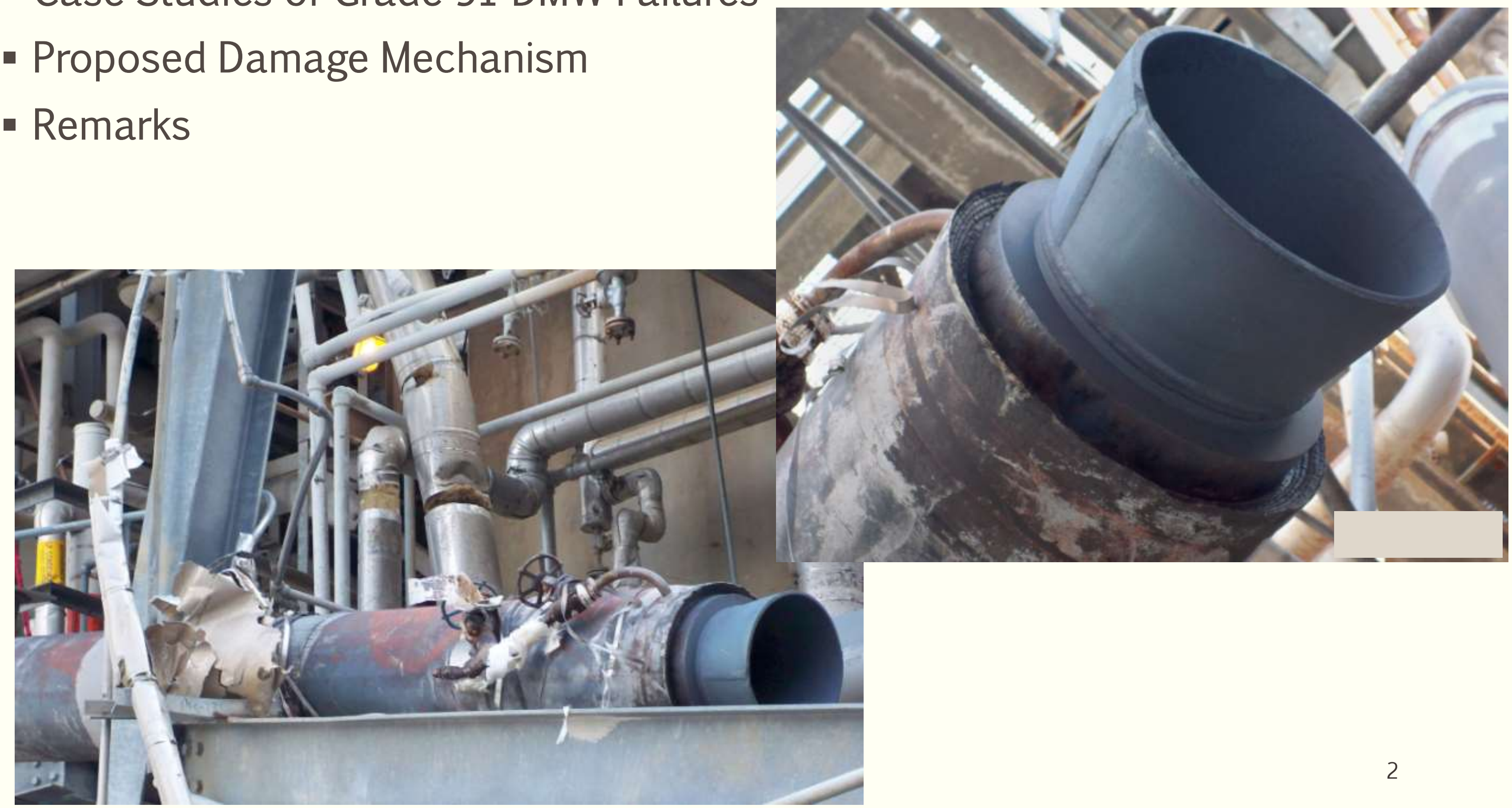
Agenda

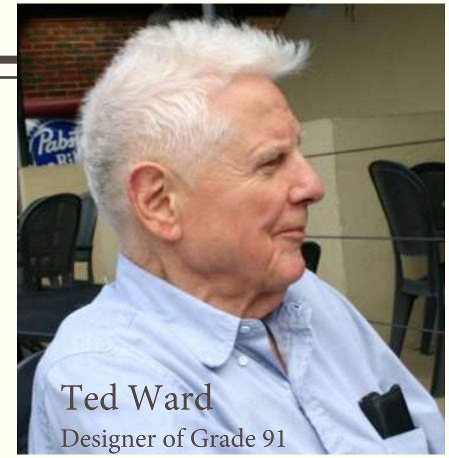
- Grade 91 Material
- Dissimilar Metal Welds (DMW)
- Case Studies of Grade 91 DMW Failures
- Proposed Damage Mechanism
- Remarks



Grade 91 Material

Combustion Engineering (CE) Designed And Developed Grade 91 Material

- Submitted the first proposal to the US-DOE in 1969 for the development of a Super 9Cr material for the sodium-cooled nuclear reactor application
- Approval was granted to develop "hardware" at CE by early 1975 under the project administration of ORNL (Oak Ridge National Laboratory)
- Established the alloy composition & demonstrated favorable properties in 1975-1980
    - Mitsubishi (MHI) & Sumitomo joined in the testing of Grade 91
    - Grade 91 was not optimized for fossil boiler applications
- Accepted by ASME as CC1943 in 1984
- ATC-CES continues research on the effect of manufacture practice on the serviceability of Grade 91 components and weldments, including DMW joints (especially creep properties).



Ted Ward
Designer of Grade 91

MODIFIED 9 Cr-1 Mo STEEL DEVELOPMENT PROGRAM PROGRESS REPORT
FOR PERIOD ENDING SEPTEMBER 30, 1978

Argonne National Laboratory
Combustion Engineering
Oak Ridge National Laboratory
Westinghouse Advanced Reactor Division

Compiled by: J. R. DiStefano

Date Published: May 1979

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

The initial work on the development of this material was published in a report entitled *A Program for the Development of Advanced Ferritic Alloys for LMFBR Application*, TR-MCD-015, issued in September 1977 by Combustion Engineering.

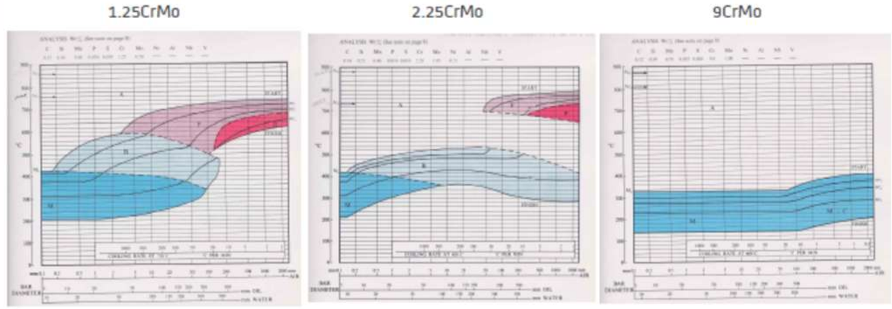
Grade 91 Material

TABLE 1
CHEMICAL REQUIREMENTS FOR FERRITIC STEEL

Grade	Composition, %									
	Carbon	Manganese	Phosphorus, max	Sulfur, max	Silicon	Chromium	Molybdenum	Titanium	Vanadium, min	Other Elements
T2 [Note (3)]	0.10–0.20	0.30–0.61	0.025	0.025	0.10–0.30	0.50–0.81	0.44–0.65	...	...	
T5	0.15 max	0.30–0.60	0.025	0.025	0.50 max	4.00–6.00	0.45–0.65	...	...	
T5b	0.15 max	0.30–0.60	0.025	0.025	1.00–2.00	4.00–6.00	0.45 –0.65	...	...	
T5c	0.12 max	0.30–0.60	0.025	0.025	0.50 max	4.00–6.00	0.45–0.65	[Note (1)]	...	
T9	0.15 max	0.30–0.60	0.025	0.025	0.25–1.00	8.00–10.00	0.90–1.10	...	...	
T11	0.05 min–0.15 max	0.30–0.60	0.025	0.025	0.50–1.00	1.00–1.50	0.44 –0.65	...	...	
T12 [Note (3)]	0.05 min–0.15 max	0.30–0.61	0.025	0.025	0.50 max	0.80–1.25	0.44–0.65	...	...	
T17	0.15–0.25	0.30–0.61	0.025	0.025	0.15–0.35	0.80–1.25	...	...	0.15	
T21	0.05 min–0.15 max	0.30–0.60	0.025	0.025	0.50 max	2.65–3.35	0.80–1.06	...	...	
T22	0.05 min–0.15 max	0.30–0.60	0.025	0.025	0.50 max	1.90–2.60	0.87–1.13	...	...	
T91	0.08–0.12	0.30–0.60	0.020	0.010	0.20–0.50	8.00–9.50	0.85–1.05	...	0.18–0.25	Cb 0.06–0.1 N 0.030–0.070 Ni 0.40 max Al 0.04 max
T92	0.07–0.13	0.30–0.60	0.020	0.010	0.50 max	8.50–9.50	0.30–0.60	...	0.15–0.25	W 1.5–2.00 Cb 0.04–0.09 B 0.001–0.006 N 0.03–0.07 Ni 0.40 max Al 0.04 max
18Cr-2Mo	0.025 max	1.00 max	0.040	0.030	1.00 max	17.5–19.5	1.75–2.50	[Note (2)]	...	N max 0.035 Ni + Cu max 1.00

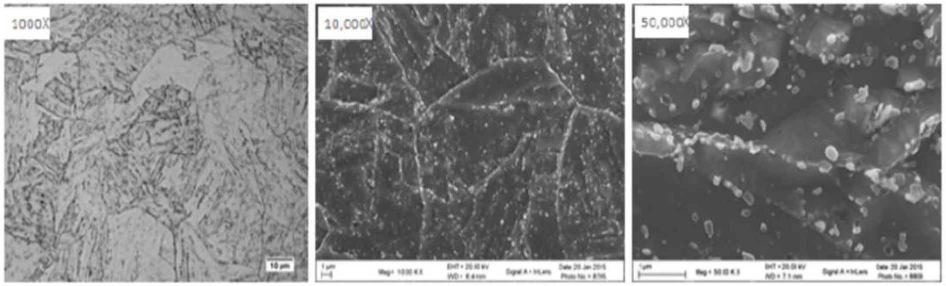
NOTES:
(1) Grade T5c shall have a titanium content of not less than four times the carbon content and not more than 0.70%.
(2) Grade 18Cr-2Mo shall have Ti + Cb = 0.20 + 4 (C + N) min, 0.80 max.
(3) It is permissible to order T2 and T12 with 0.045 max Sulfur.

As Alloy content (in this case) increases, the nose of the CCT diagram begins to shift to the right allowing martensite to be formed with slower critical cooling rate.



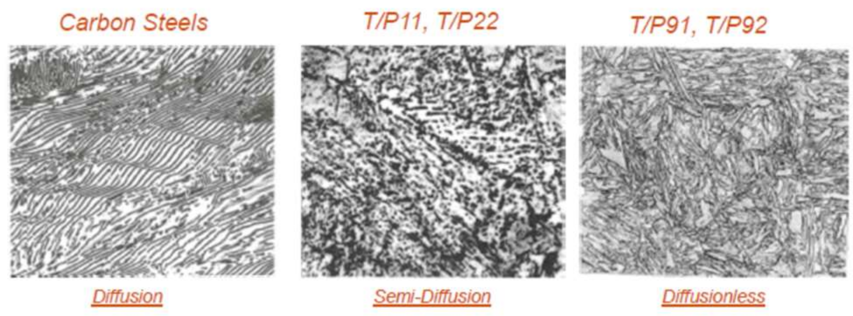
Increasing Alloy Content

Grade 91 Material – Tempered Martensite



Grade 91 Base Metal in N&T condition

Austenite



Diffusion → Fe_3C

Dissimilar Metal Weld (DMW)

In utility industry, a dissimilar metal weld is defined as a weld between two different alloy systems.

- Ferritic steel and austenitic stainless steel
  - Historically: Grade 22 to TP3XXH in tube butt welds with austenitic filler (shorter service life), then Ni-based filler (significantly improved service life)
  - More recently: Grades 91 and 92 to TP3XXH and Super 304H in tube and pipe applications with Ni-based filler
- Improving efficiency
  - Save material cost
  - DMW @ higher temperature locations
  - Unit operates in cyclic conditions

Complex Welding Metallurgy in DMW Joints

- <u>Macrostructure</u>
  - *Five zones across joint*

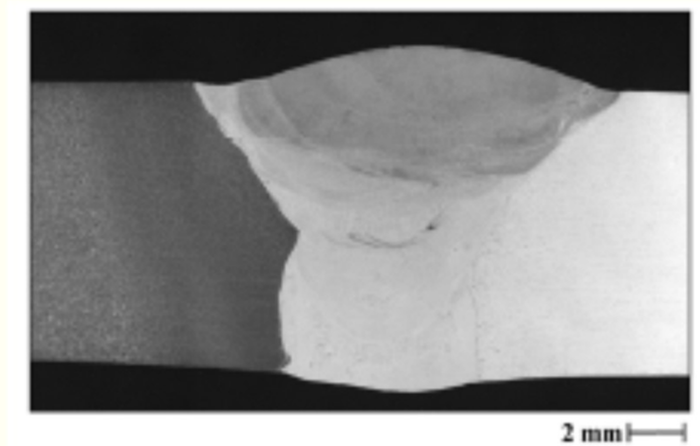
    BM1 = Grade 91

    Heat-Affected Zone

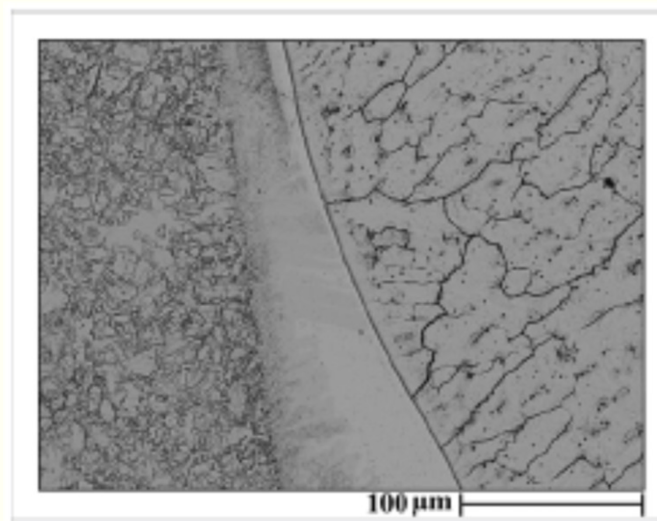
    Weld Deposit

    Heat-Affected Zone

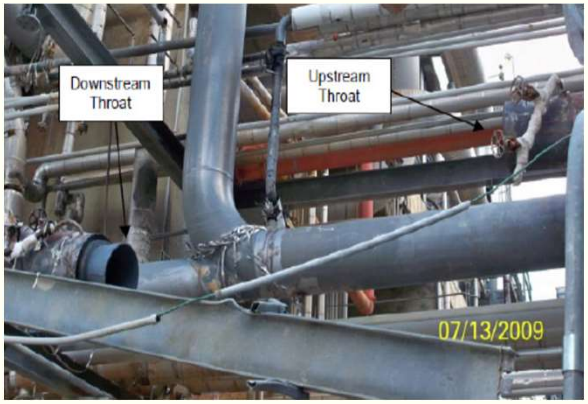
    BM2 = TP3XXH



- <u>Microstructure</u> *(P91 Side)*
  - Weld Deposit
  - Unmixed zone /Partially melted zone
  - Coarse-grained heat-affected zone
  - Fine grained heat-affected zone
  - Intercritical heat-affected zone
  - Subcritical heat-affected zone



Why is Grade 91 DMW Joints a Concern?



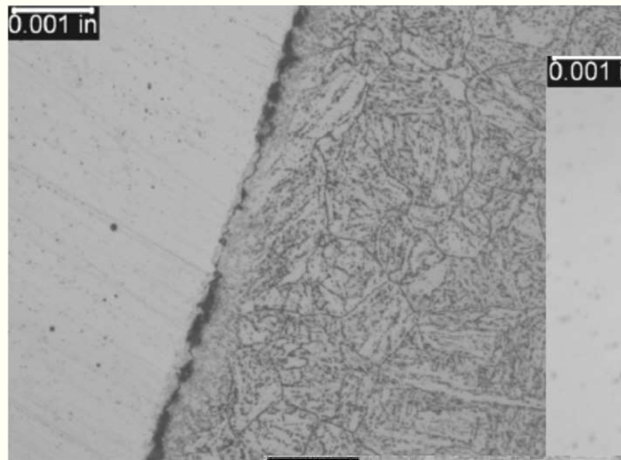
- Grade 91 DMW failures have no warning – safety hazards.
- Low-ductility rupture on Grade 91 side – can cause significant consequential damage.
- Grade 91 DMW joints revealed a short service life as little as 16,000 hours (~2 years).
- Grade 91 DMW failures have been attributed to a number of different factors with little to no root cause analysis – little understanding the damage mechanism.
- Laboratory Uniaxial creep testing failed to duplicate the damage mode.
- Relatively low percentage of Grade 91 DMW failed in service.

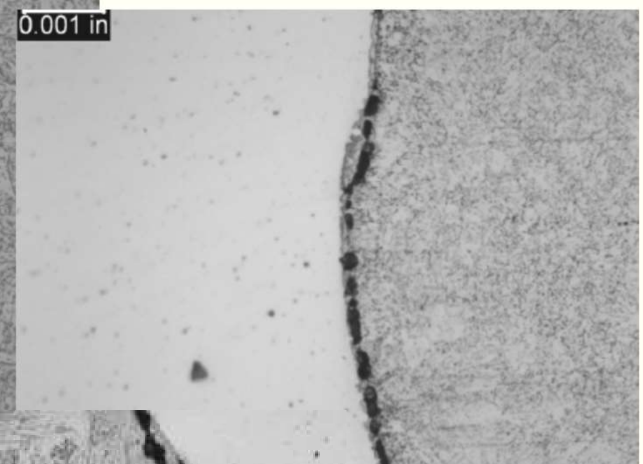
List of Known Grade 91 DMW Failures

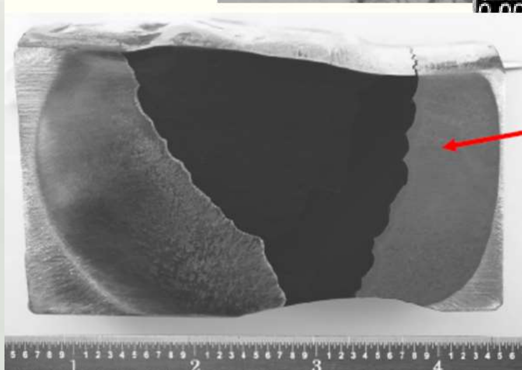
- SH Outlet Lead: Supercritical Boiler, 348 mm OD x 60 mm wall, P91-to-TP321H with Inco A filler, 540°C, 40,000 hours
- Main Steam Lead: HRSG, 356 mm OD x 32 mm wall, P91-to-TP304H with Inconel filler, 566°C, 125,000 hours
- Steam outlet pipe A: OTC, 115 mm OD x 14 mm wall, P91-to-TP316H with Inconel filler, 545°C, 70,000 hours
- Steam outlet pipe B: OTC, 115 mm OD x 14 mm wall, P91-to-TP321H with UTP 068 HH filler, 530°C, ~2 years
- Steam outlet pipe C: OTC, 115 mm OD x 14 mm wall, P91-to-TP321H with UTP 068 HH filler, 545°C, ~2 years
- Steam outlet pipe D: OTC, 115 mm OD x 14 mm wall, P91-to-TP321H with UTP 068 HH filler, 530°C, ~2 years
- Steam outlet pipe E: CT intercooler, 114 mm OD x 17 mm wall, P91-to-TP316H with Alloy 625 filler, 538°C, 16,550 hours
- Steam outlet pipe F: CT intercooler, 114 mm OD x 17 mm wall, P91-to-TP321H with Alloy 625 filler, 538°C, ~10 years
- Flow Element A: HP Superheater piping, 406 mm OD x 27 mm wall, P91-to-TP316H with Inco 182 filler, 507°C, ~8 years
- Flow Element B HP Superheater piping, 327 mm OD x 29 mm wall, P91-to-F304 with ENiCrFe-3 filler, 538°C, ~14 years
- SH Tube Attachments: Subcritical boiler, 57 mm OD x 6 mm wall, T91 welded with A97 Grade HH lugs and Inco A filler, 538°C, after 23,000 hours, more than 800 lugs cracked or failed out.
- SH Tube Attachments: Subcritical boiler, 57 mm OD x 6.6 mm wall, T91 welded with 321H lugs and Inco A filler, 540°C, after 72,000 hours, over 1000 lugs cracked or failed out.
-

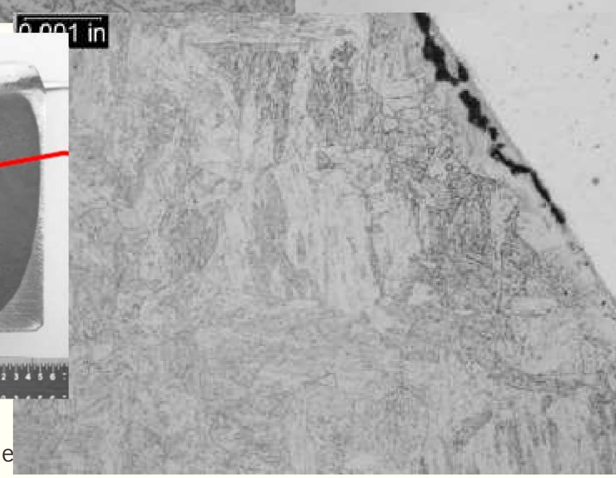
Grade 91 DMW Case Study-1

System	DMW Location	Temperature (°C)	Service Hours	Diameter (mm)	Wall (mm)	Ferritic Material	Austenitic Material	Filler Material
SC Boiler	SH Outlet Lead	540	40,000	348	60	P91	TP321H	Inco A

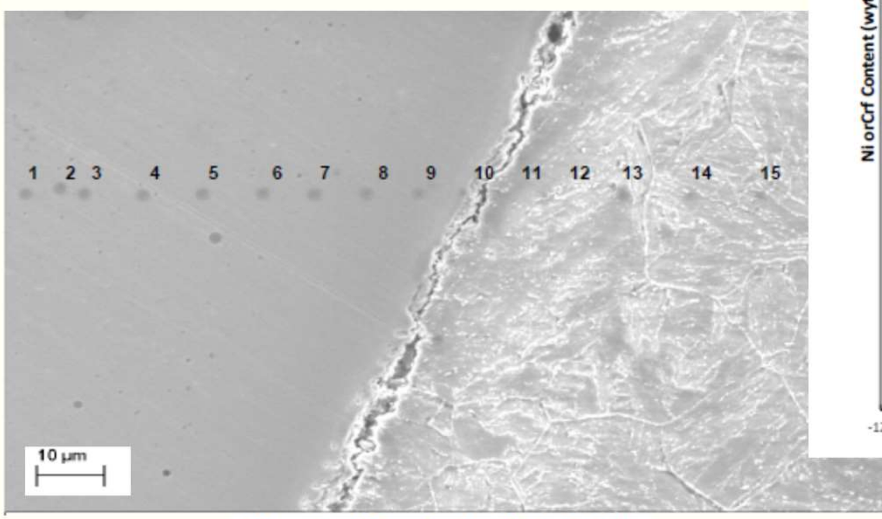


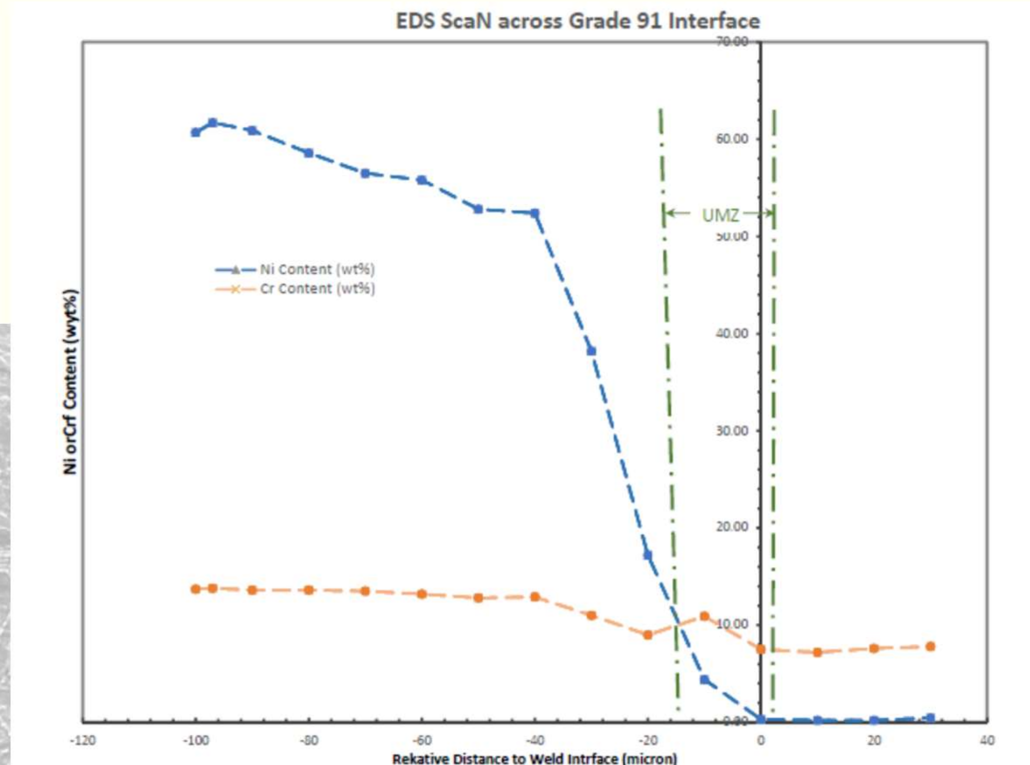






Grade 91 DMW Case Study-1





Chemical Analysis (Weight %)

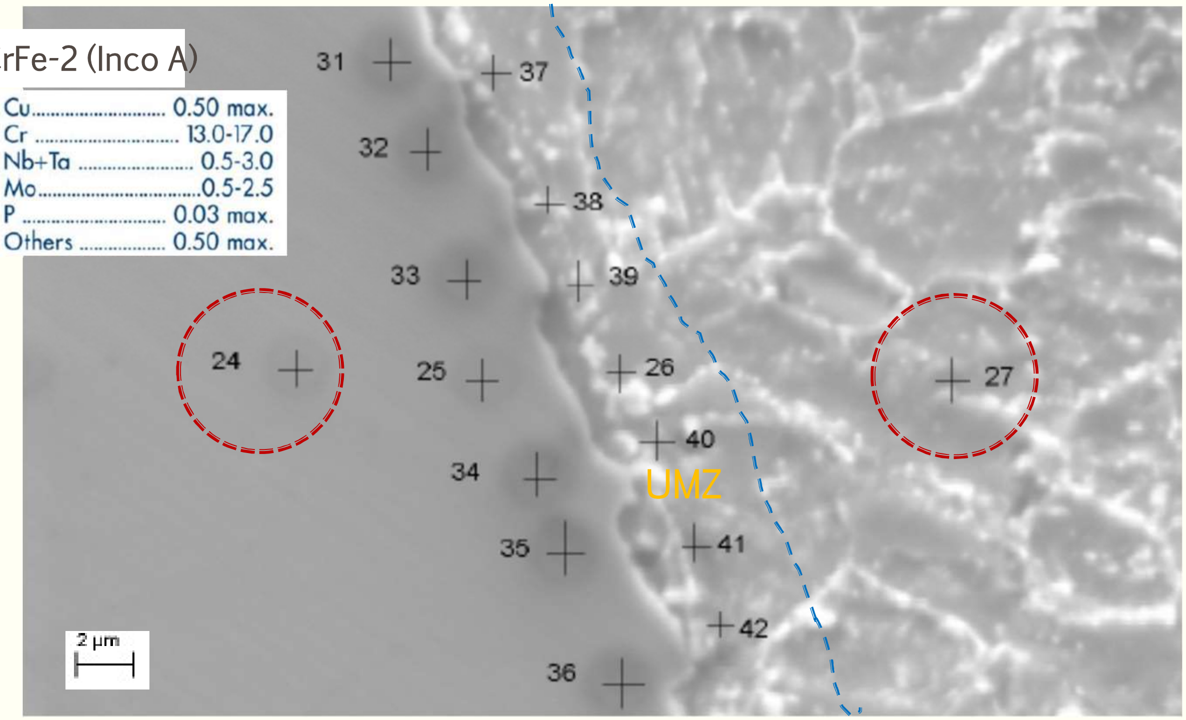
Elem.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si	0.6	0.7	0.5	0.5	0.5	0.7	0.3	0.4	0.3	0.3	*3.1*	0.4	0.3	0.4	0.3
V	0.1	ND	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	*0.3*	0.3	0.2	0.3	0.3
Cr	13.7	13.8	13.6	13.6	13.5	13.2	12.8	12.9	11.0	9.0	*10.9*	7.5	7.2	7.6	7.8
Mn	1.5	1.6	1.2	1.2	1.4	1.2	0.9	1.1	0.9	0.6	*0.6*	0.4	0.5	0.4	0.5
Fe	17.2	15.3	19.4	21.2	23.1	23.6	29.2	28.5	44.5	69.5	*70.0*	86.3	88.7	88.9	88.2
Ni	60.7	61.7	60.9	58.6	56.5	55.8	52.8	52.1	38.2	17.2	*4.4*	0.3	0.2	0.2	0.4
Cb	1.1	2.1	0.8	0.9	1.3	1.9	0.7	0.7	0.4	0.2	*0.1*	0.3	0.3	0.2	0.3
Mo	1.8	1.6	1.6	1.2	1.5	1.5	1.2	1.5	0.9	0.6	*1.5*	0.5	0.3	0.5	0.7

Grade 91 DMW Case Study-1

AWS A5.11 ENiCrFe-2 (Inco A)

Ni+Co.................... 62.0 min.
C .... 0.10 max.
Mn............................... 1.0-3.5
Fe............................ 12.0 max.
S .... 0.02 max.
Si .... 0.75 max.

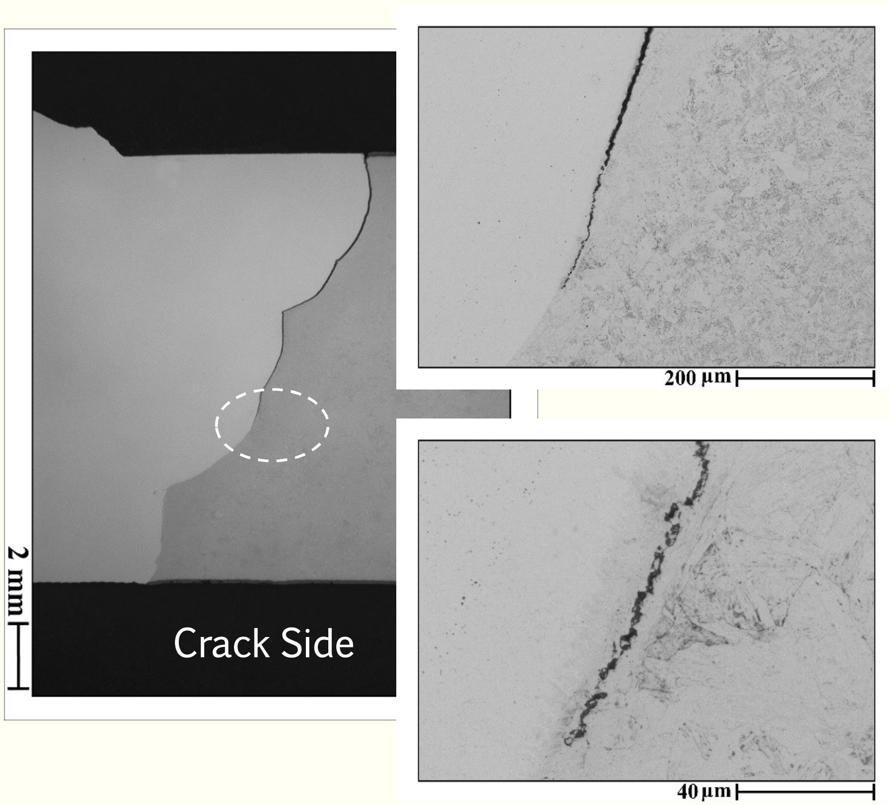
Cu.......................... 0.50 max.
Cr 13.0-17.0
Nb+Ta 0.5-3.0
Mo..................................0.5-2.5
P .... 0.03 max.
Others .... 0.50 max.

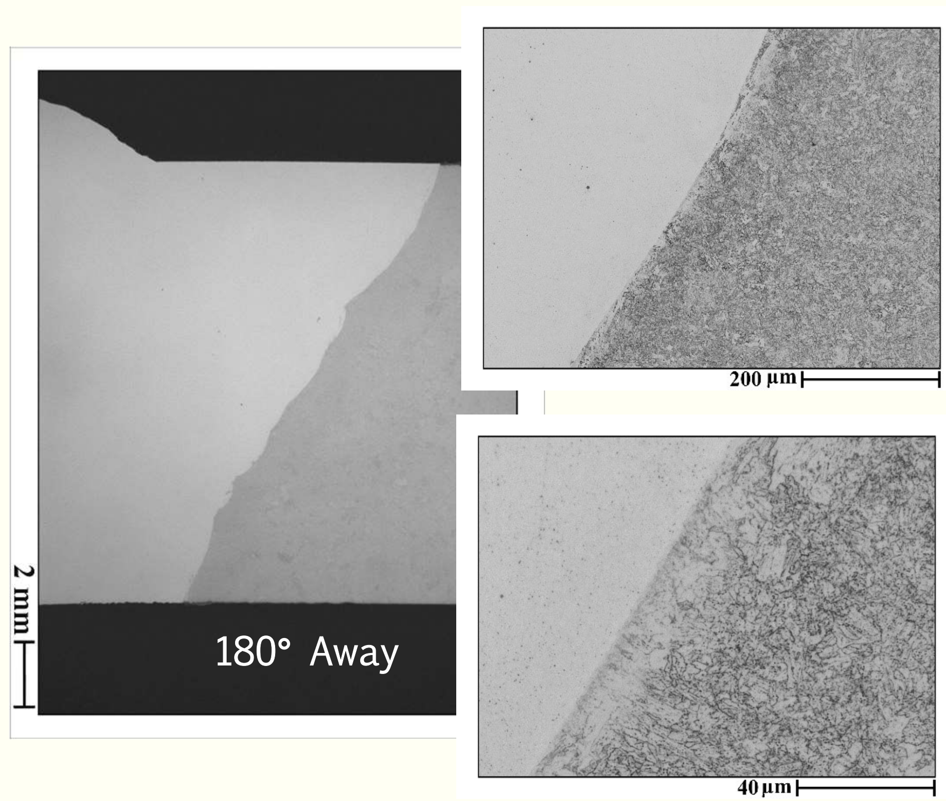


Elem.	24	27	31	32	33	34	35	36	37	38	39	40	41	42
Si	0.5	0.3	0.37	0.31	0.32	0.36	0.34	0.33	1.10	0.48	0.40	0.55	1.26	1.04
V	0.2	0.1	0.16	0.24	0.16	0.25	0.19	0.17	0.35	0.34	0.20	0.23	0.54	0.41
Cr	12.0	7.0	9.89	10.05	9.88	10.25	10.14	10.21	10.15	8.99	8.34	8.26	11.60	10.45
Mn	0.8	0.4	0.61	0.57	0.99	0.52	0.65	1.50	0.53	0.52	0.53	0.54	0.63	0.47
Fe	52.2	89.1	59.4	60.4	60.3	57.7	57.9	59.8	76.8	81.8	85.6	83.5	74.7	77.9
Ni	30.7	1.0	25.4	26.3	25.0	27.6	27.3	25.8	5.88	4.85	3.70	4.04	5.14	4.40
Cb	0.9	0.1	0.44	0.25	0.35	0.87	0.47	0.41	0.22	0.11	0.55	0.12	0.30	0.19
Mo	1.2	0.5	1.13	0.65	0.81	1.04	1.08	0.55	1.78	0.96	0.75	1.09	2.79	1.97

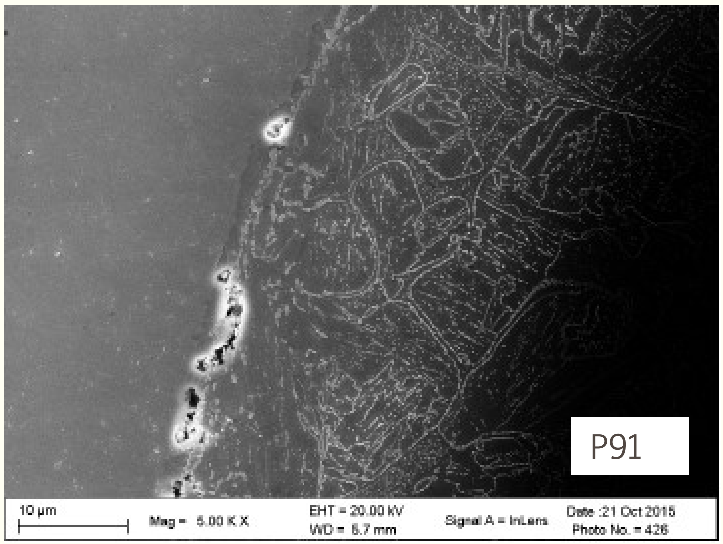
Grade 91 DMW Case Study-2

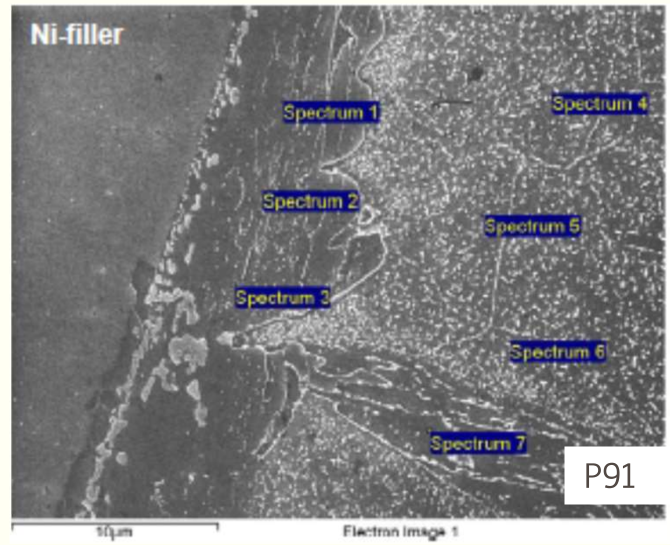
System	DMW Location	Temperature (°C)	Service Hours	Diameter (mm)	Wall (mm)	Ferritic Material	Austenitic Material	Filler Material
OTC	Steam Outlet Pipe	545	~70,000	115	14	P91	TP316H	Inconel

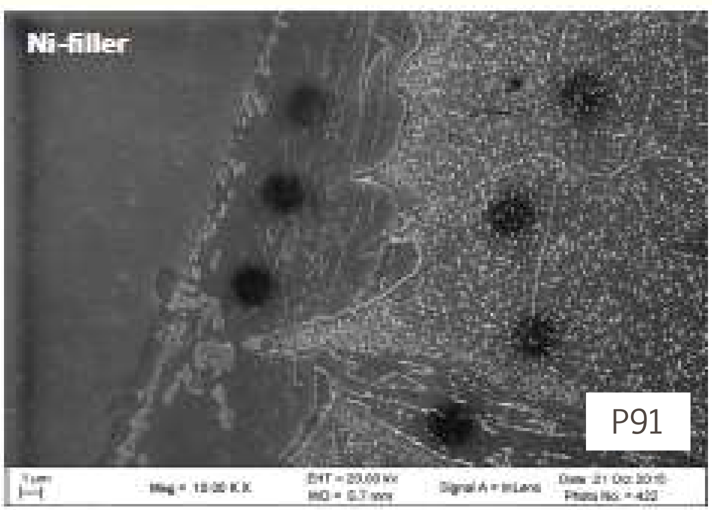




Grade 91 DMW Case Study-2

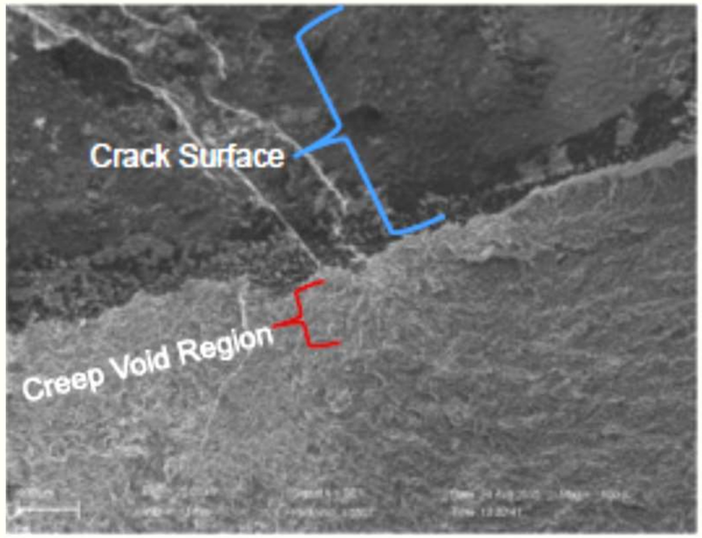


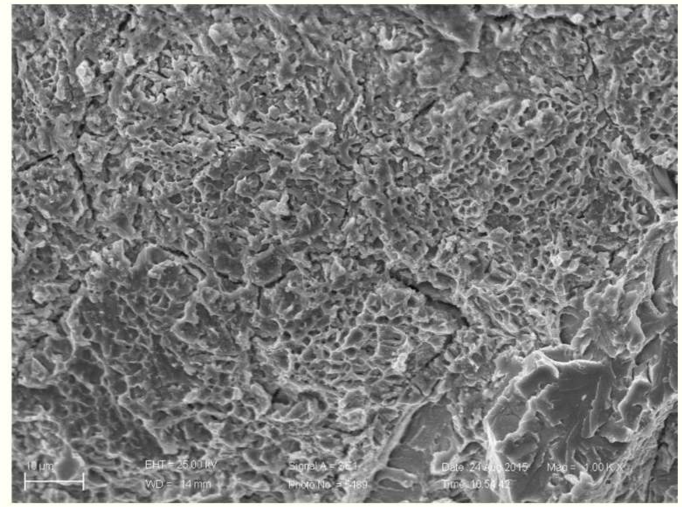


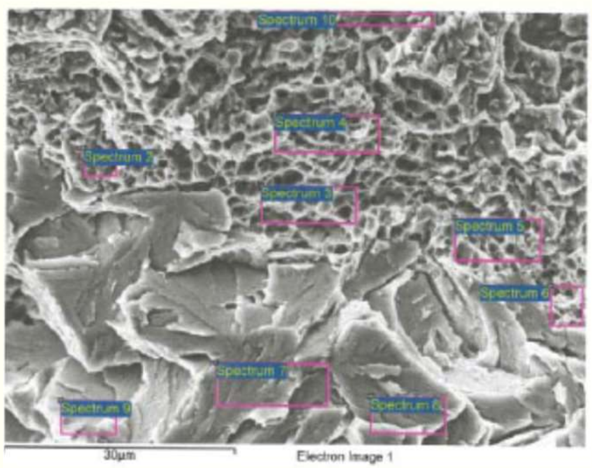


		Si	Cr	Fe	Ni	Mo
Spectrum 1	Yes		8.05	90.59	**1.37**	
Spectrum 2	Yes		8.72	90.05	**1.23**	
Spectrum 3	Yes	0.51	8.04	89.82	**1.63**	
Spectrum 4	Yes	0.62	8.12	90.06		1.19
Spectrum 5	Yes	0.43	8.57	91.01		
Spectrum 6	Yes		8.78	91.22		
Spectrum 7	Yes	0.71	8.41	90.88		

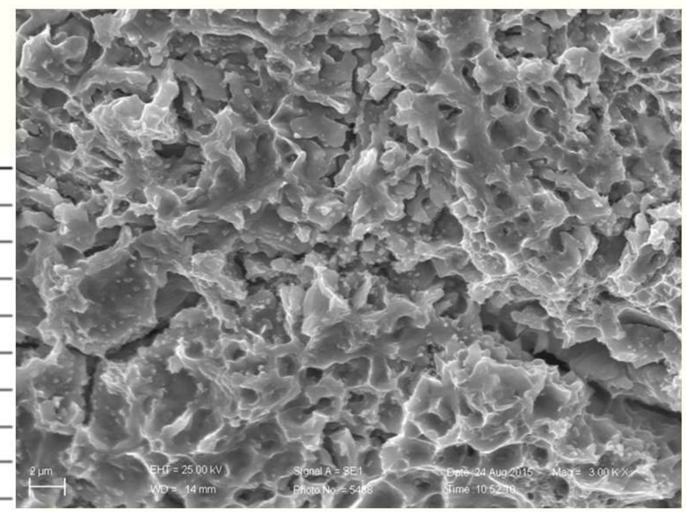
Grade 91 DMW Case Study-2





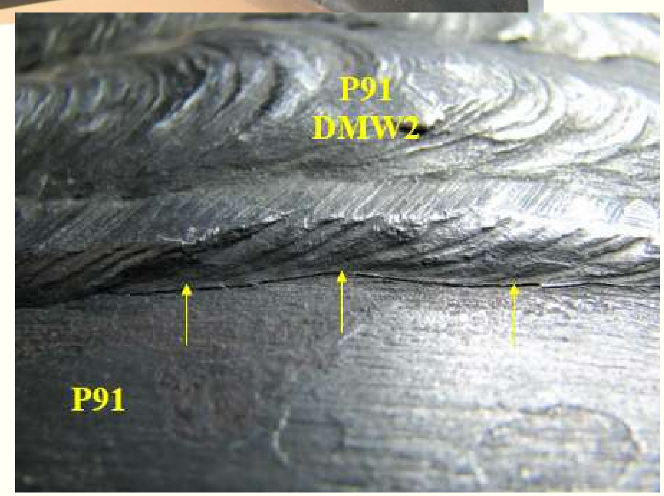


Spectrum	O	Cr	Fe	Ni
Spectrum 2		9.30	89.49	1.21
Spectrum 3		8.95	88.75	2.30
Spectrum 4	2.78	9.34	85.32	2.56
Spectrum 5		10.16	86.85	2.99
Spectrum 6		10.49	86.18	3.33
Spectrum 7		8.63	89.69	0.84
Spectrum 8		9.27	90.72	0.01
Spectrum 9		9.44	90.17	0.39
Spectrum 10	0.85	9.10	90.05	

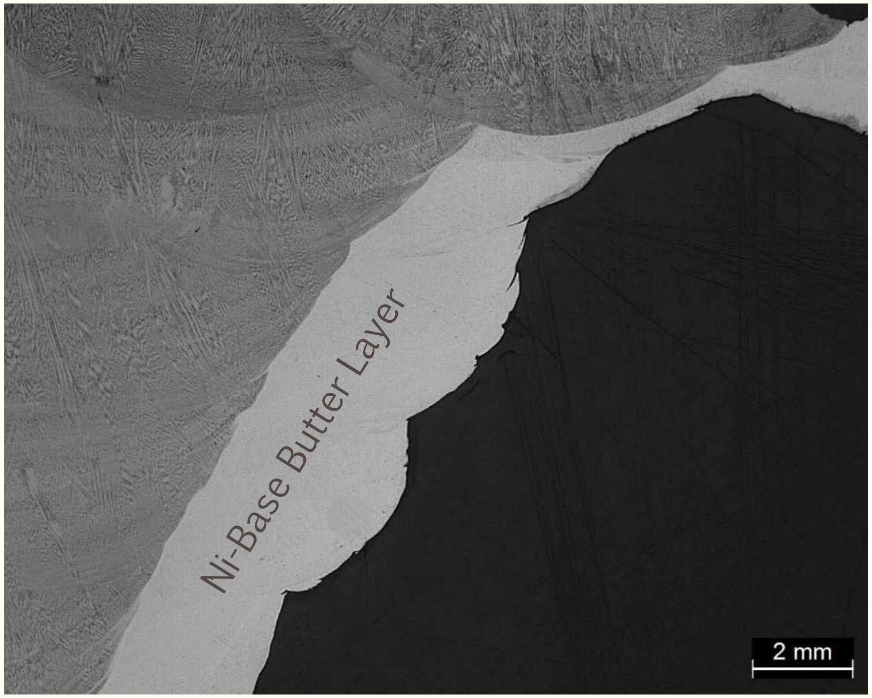


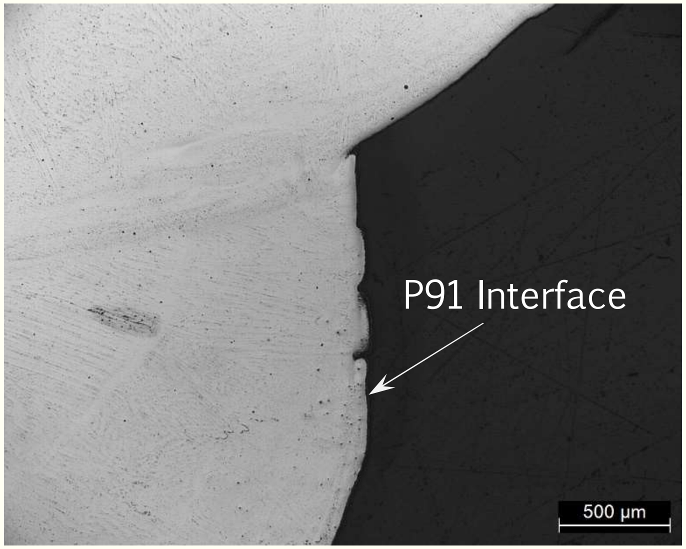
Grade 91 DMW Case Study-3

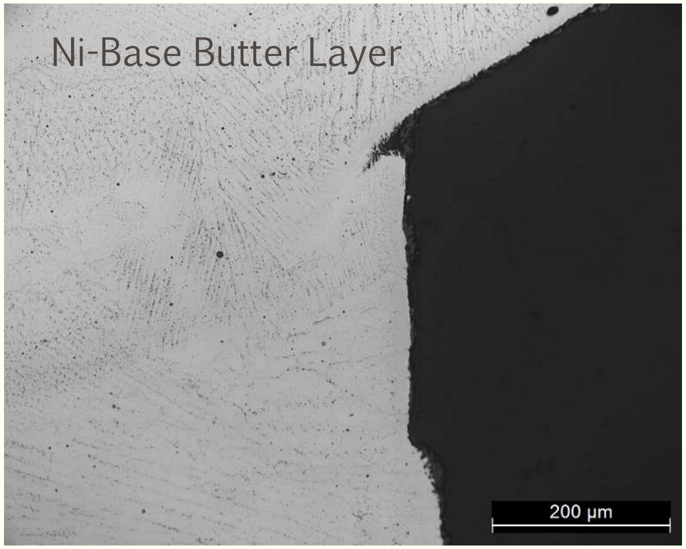
System	DMW Location	Temperature (°C)	Service Time	Diameter (mm)	Wall (mm)	Ferritic Material	Austenitic Material	Filler Material
Flow Element	Main Stem Pipe	538	14 years	327	29	P91	F304	ENiCrFe-3



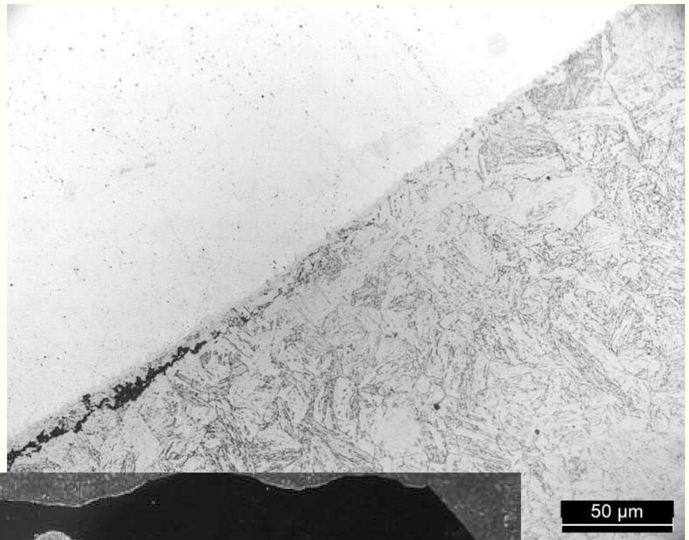
Grade 91 DMW Case Study-3

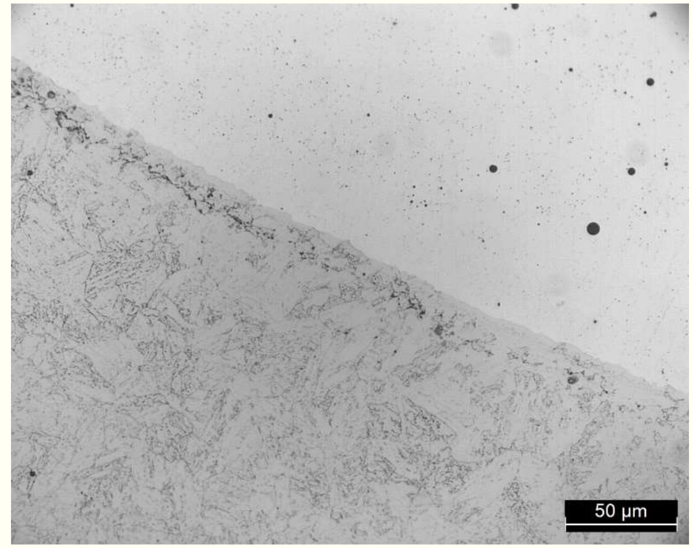


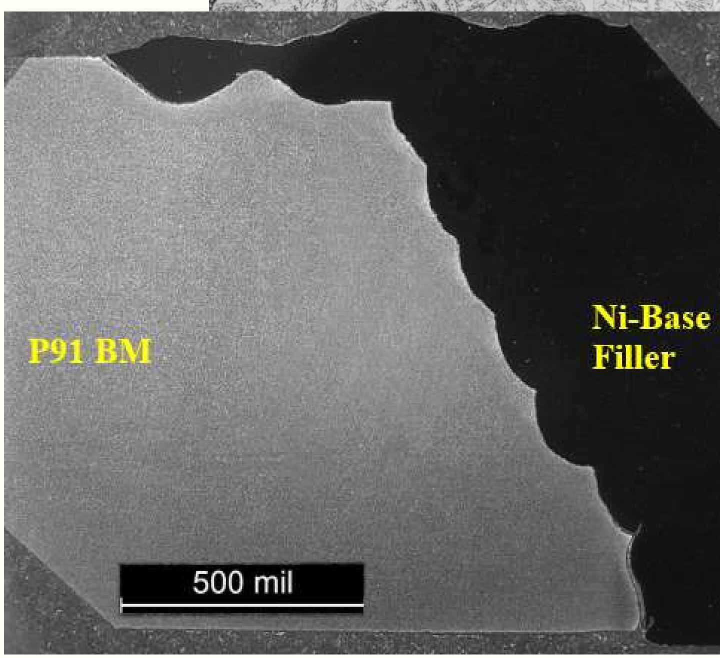


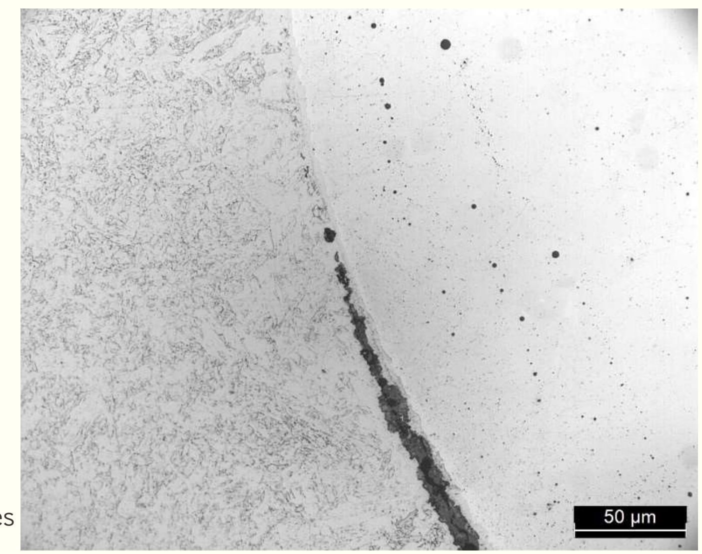


Grade 91 DMW Case Study-3

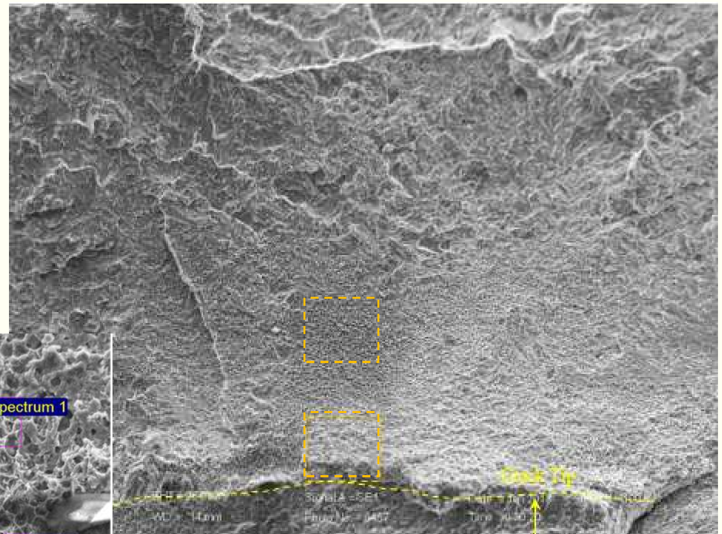


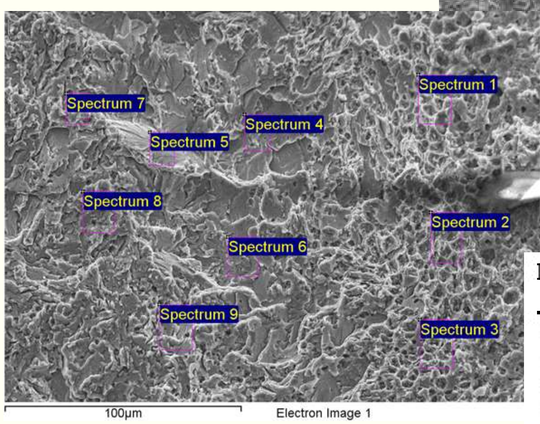


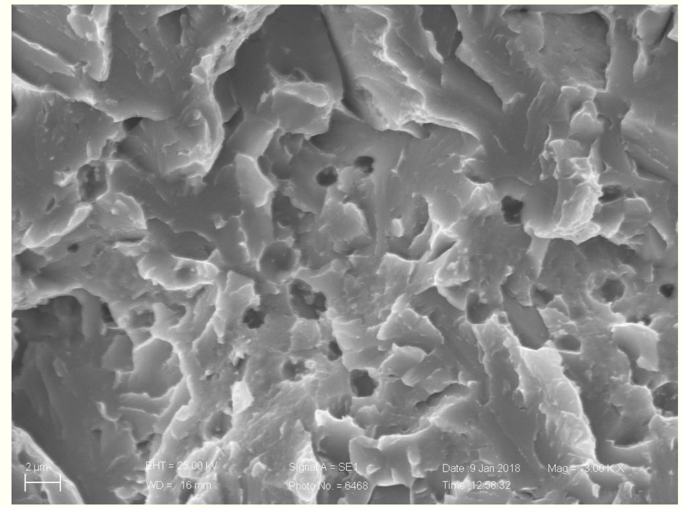




Grade 91 DMW Case Study-3



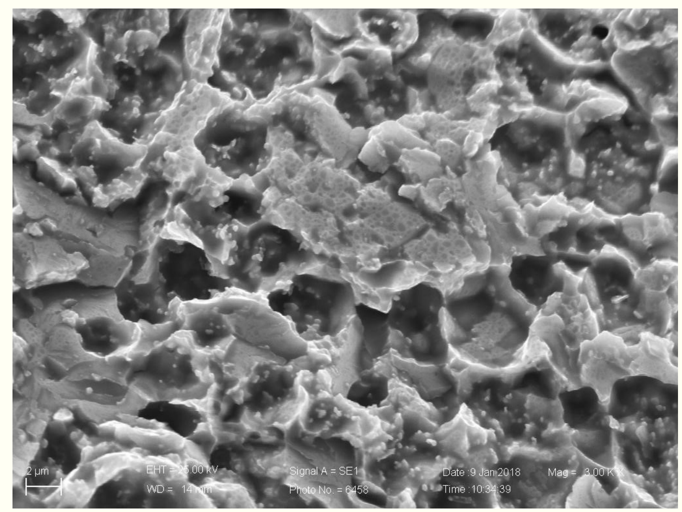




Processing option : All elements analysed (Normalised)

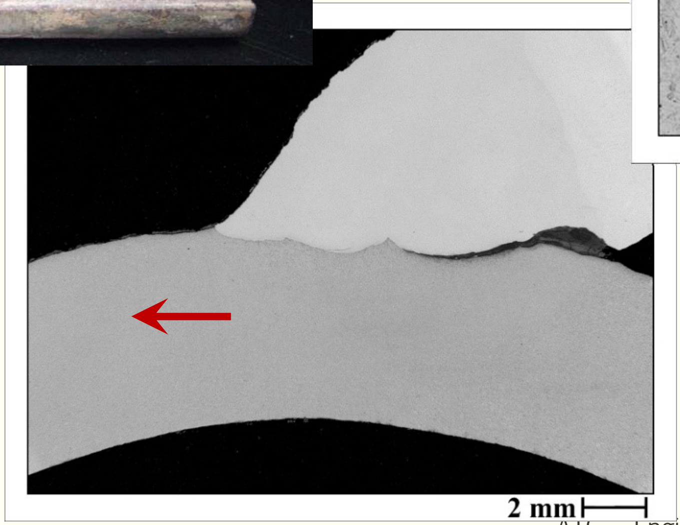
Spectrum	In stats.	Cr	Fe	Ni	Total
Spectrum 1	Yes	11.35	86.01	2.64	100.00
Spectrum 2	Yes	10.75	87.42	1.84	100.00
Spectrum 3	Yes	10.32	86.39	3.29	100.00
Spectrum 4	Yes	9.10	89.34	1.56	100.00
Spectrum 5	Yes	9.73	88.80	1.47	100.00
Spectrum 6	Yes	9.70	88.76	1.54	100.00
Spectrum 7	Yes	10.34	87.43	2.23	100.00
Spectrum 8	Yes	10.66	86.03	3.32	100.00
Spectrum 9	Yes	10.78	86.36	2.86	100.00
Mean		10.30	87.39	2.30	100.00
Std. deviation		0.69	1.30	0.75	
Max.		11.35	89.34	3.32	
Min.		9.10	86.01	1.47	

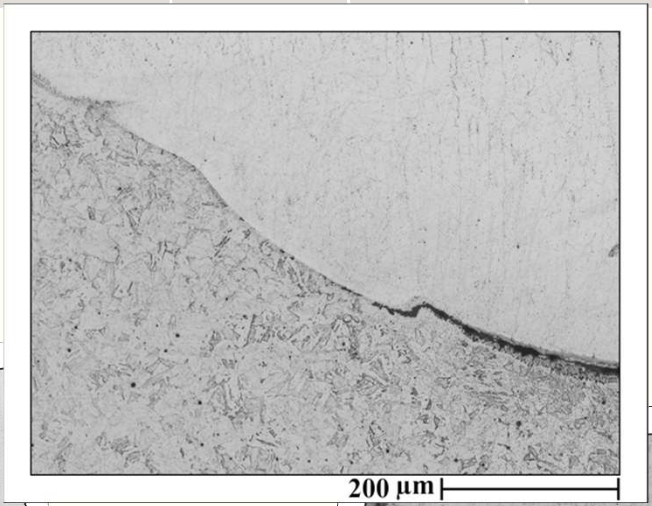
All results in weight%

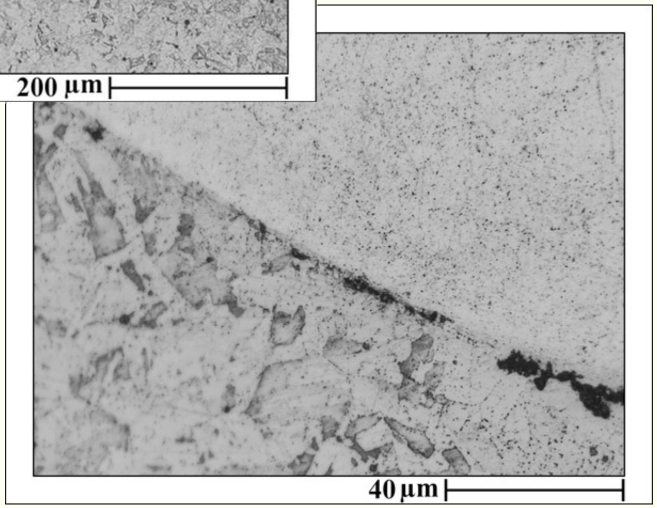


Grade 91 DMW Case Study-4

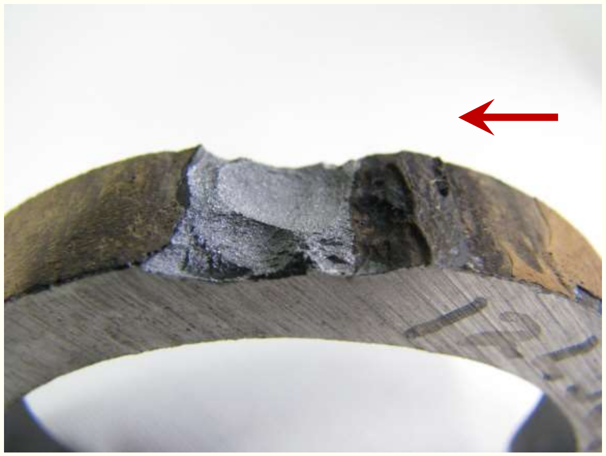
System	DMW Location	Temperature (°C)	Service Time	Diameter (mm)	Wall (mm)	Ferritic Material	Austenitic Material	Filler Material
Subcritical Boiler	SH Tube Lug	538	23,000 hrs	57	6	T91	Grade HH	Inco A

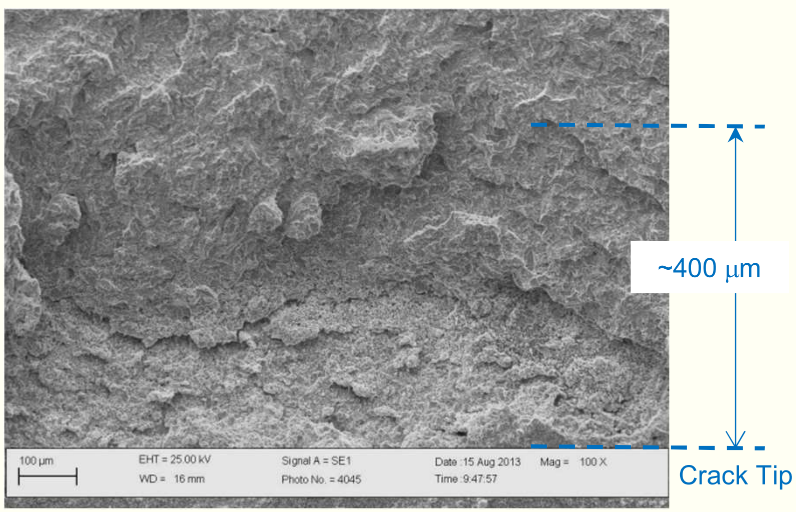


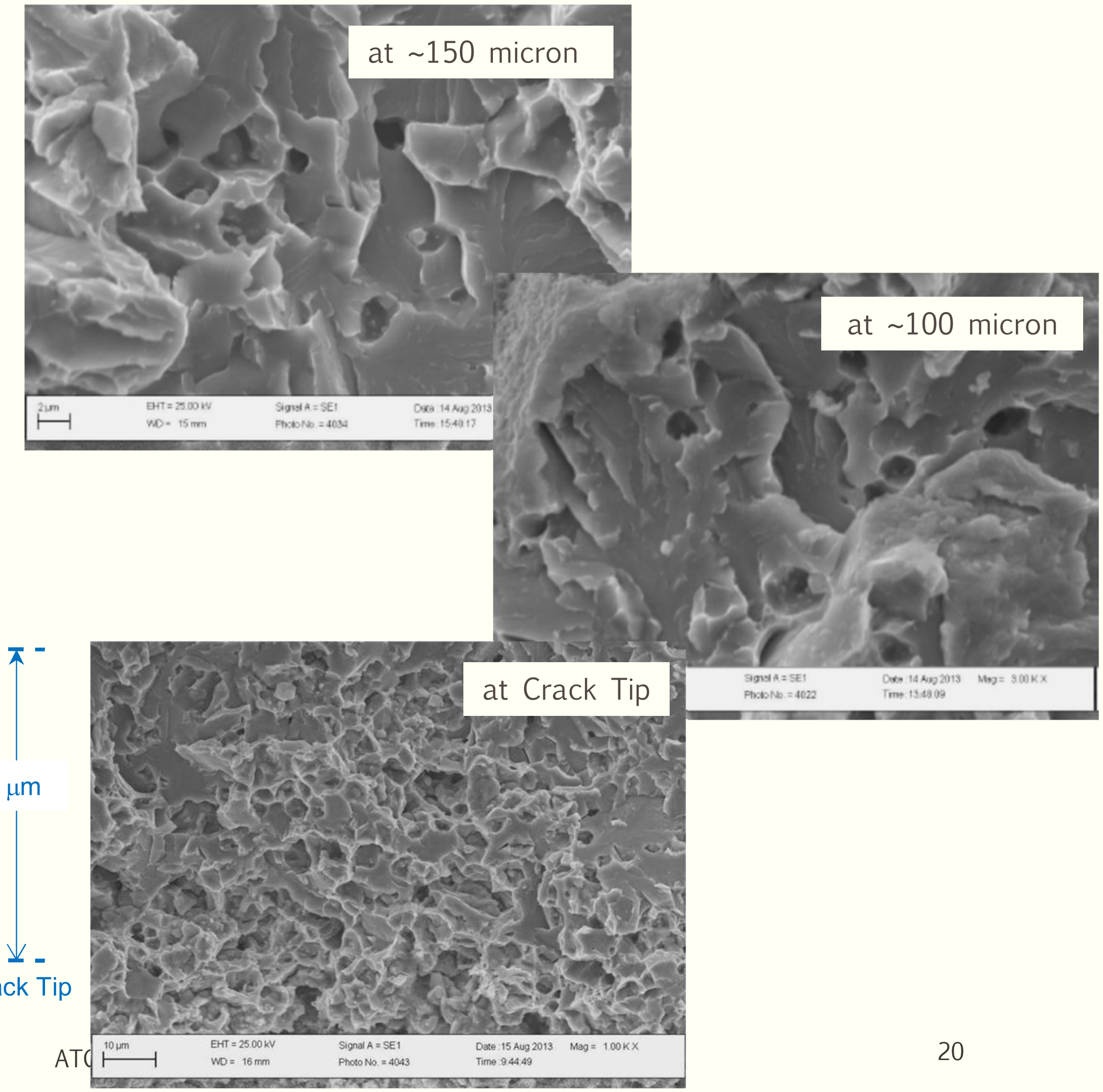




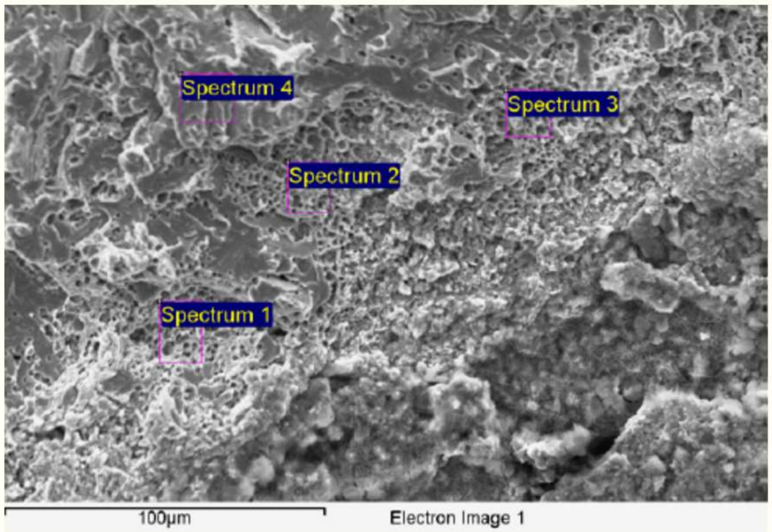
Grade 91 DMW Case Study-4

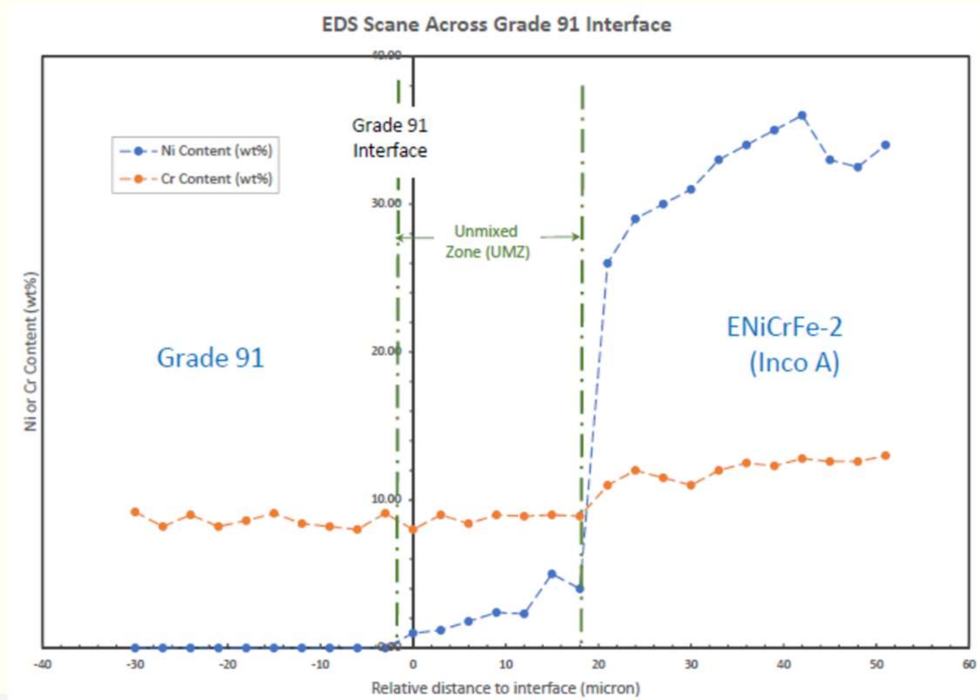






Grade 91 DMW Case Study-4





Spectrum	In stats.	Si	V	Cr	Fe	Ni	Mo	Total
Spectrum 1	Yes	0.18	0.19	9.25	88.56	1.24	0.58	100.00
Spectrum 2	Yes	0.32	0.32	9.05	87.85	1.73	0.72	100.00
Spectrum 3	Yes	0.05	0.28	9.03	88.30	1.43	0.92	100.00
Spectrum 4	Yes	0.32	0.23	9.20	89.02	0.49	0.74	100.00
Mean		0.22	0.25	9.13	88.43	1.22	0.74	100.00
Std. deviation		0.13	0.06	0.11	0.49	0.53	0.14	
Max.		0.32	0.32	9.25	89.02	1.73	0.92	
Min.		0.05	0.19	9.03	87.85	0.49	0.58	

All results in weight%

Summary of Characteristics of Grade 91 DMW Failures

- All cases of Grade 91 DMW failures reveal a common and similar damage pattern.
- Grade 91 DMW failures are a non-ductile fracture that occurs along the toe of the DMW joint on Grade 91 side. Generally, the damage is concentrated on one side of the joint with the damage level on the opposite side significantly lower or none.
- The damage in Grade 91 DMW joints along the Gr 91 interface occurs in the unmixed zone (UMZ).
- Damage can initiate from either OD or ID surface or at mid-wall of Grade 91 DMW joints depending on stress state. In the most cases, cracking starts from the OD of the joints.
- Creep cavities are either spawned in stress-concentration zone in front of crack tip or formed in the areas where the metallurgical condition (microstructure, temperature and stress) is suitable.

Summary of Characteristics of Grade 91 DMW Failures

- The creep cavitation zone in the front of the crack tip is approximately 20 – 100 μm deep for P91 DMW joints and up to 400 μm deep for T91 attachments. The creep damage in front of the crack tip is leading the crack propagation behavior.

- The damage mode is consistent with the creep-dominated mechanism.

- In the areas where creep cavities are present, 1–4% Ni is detected in all cases. The Ni distribution across the UMZ is not uniform and increase toward the solidification terminals of the UMZ. The A_{c1} temperature of the UMZ is lower than the specified PWHT temperature (730 - 775°C) for Grade 91 welds.

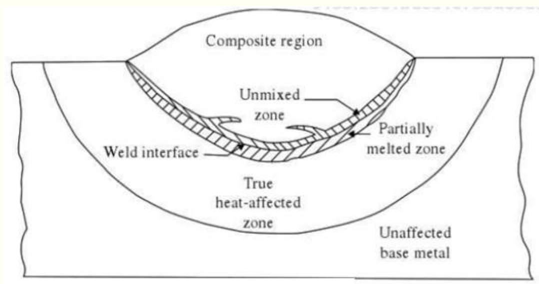
  The area adjacent to the UMZ in the weld deposit (transition zone) has the composition closer to an Incoloy grade or a 300-series stainless grade in which the thermal-mechanical properties are considerably different from those of the surrounding areas.

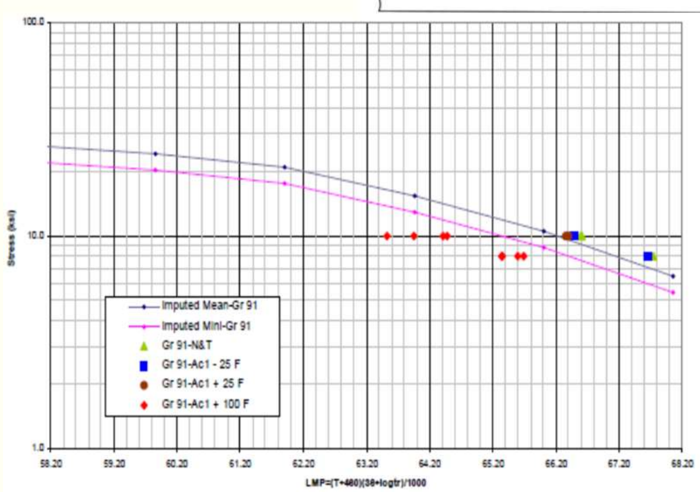
Hypothesis – Damage Mechanism of Grade 91 DMW Joints

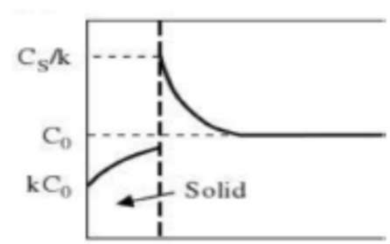
- The proposed mechanism for the damage development in Grade 91 DMW joints include <u>three parts</u>:
  - Formation of a creep-weak zone in the UMZ along Grade 91 interface
  - Unique mismatch behavior along Grade 91 interface
    - Creep strength mismatch
    - Thermal-mechanical mismatch
  - Necessary stress state

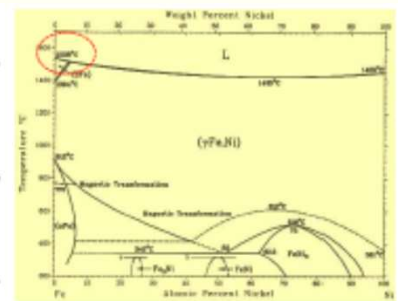
Hypothesis –
Damage Mechanism of Grade 91 DMW Joints

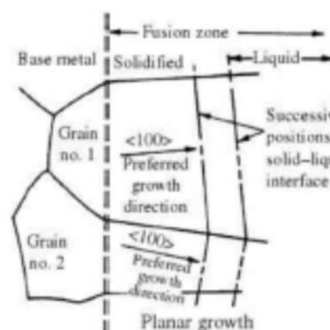
- <u>Formation of a creep-weak zone in the UMZ along Grade 91 interface</u>
  - Ni enrichment in UMZ is the results of planar growth and partitioning effect (k<1)
  - 1-4%Ni in UMZ significantly decrease A_{C1} below PWHT temperature for Grade 91 welds
  - During PWHT, UMZ suffers partial phase transformation
  - Partially transformed UMZ lose creep strength considerably - a creep-weak zone

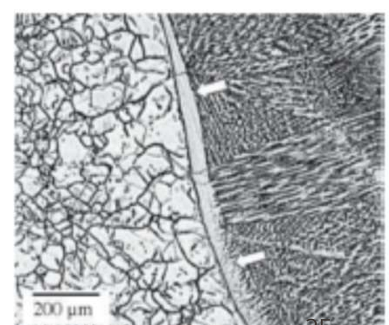






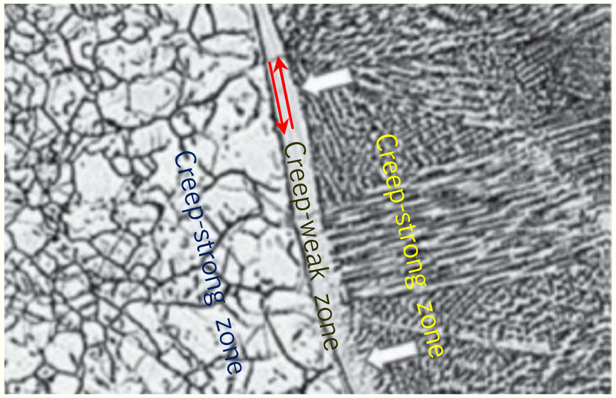






Hypothesis –
Damage Mechanism of Grade 91 DMW Joints

- <u>Unique mismatch behavior along Grade 91 interface</u>
  - Creep strength mismatch – between the UMZ and the surrounding areas due to creep strength differential – significant shear stress in UMZ under load.

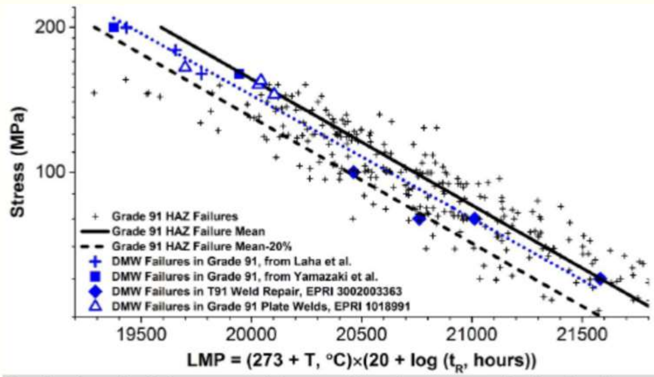


  - Thermal-mechanical mismatch – between the transition zone and the surrounding areas due to thermal-expansion coefficient differential. The transition zone adjacent to the UMZ has its composition similar to Incoloy grade or an austenitic stainless steel grade material.

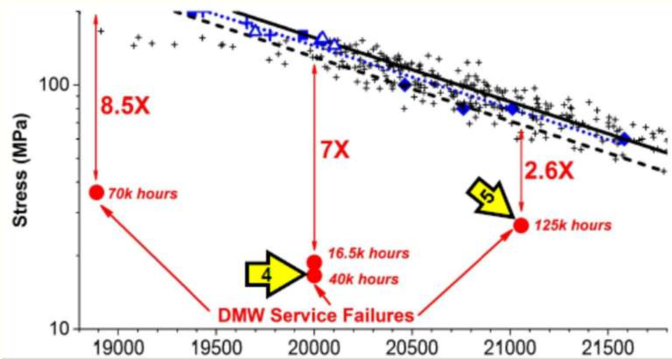
Instantaneous Coefficient of Thermal Expansion X 10^{-8} (in/in/F)					
Materials	Grade 91	Grade 22	TP304h	Inconel 625	Incoloy 800
Ambient	5.8	6.4	8.5	6.7	7.9
1000°F	7.8	9.4	10.3	9.4	10.3
Mismatch with Gr. 91 @ 1000°F	---	1.6	2.5	1.6	2.5
Mismatch with Gr. 22 @ 1000°F	1.6	---	0.9	---	0.9

Hypothesis –
Damage Mechanism of Grade 91 DMW Joints

- <u>Necessary Stress State</u>
  - Damage in Grade 91 DMWs is always concentrated on one side of the joint with the damage level on the opposite side significantly lower or none – Bending load.
  - Laboratory simulation tests by Combustion Engineering (CE) and EPRI could not duplicate the true failure mode as happened in SH and RH DMW joints using a uniaxial load unless a bending load is applied.
  - Grade 91 DMW failures in service cannot be explained on the basis of the literature results for uniaxial creep tests.



In simple uniaxial, cross-weld creep there is not a marked reduction for fusion line failures from HAZ failures in Grade 91 steel



There is a marked reduction in performance for service failures from the database of DMW fusion line failures

Bending load in a cyclic mode is a necessary stress condition for development of Grade 91 DMW interface damage.

Remarks

- The failure of Grade 91 DMW joints is the direct result of creep-dominated damage in the unmixed zone along the Grade 91 interface.

- The Grade 91 interface in Grade 91 DMW joints contains unique metallurgical conditions, which leads to formation of a creep weak zone during DMW manufacture with significant creep-strength mismatch and thermal-mechanical mismatch.

- It must be recognized that the Grade 91 interface is a narrow zone (<100 μm). Bending stress in a cyclic mode is a necessary stress state for development of the damage along the Grade 91 interface.

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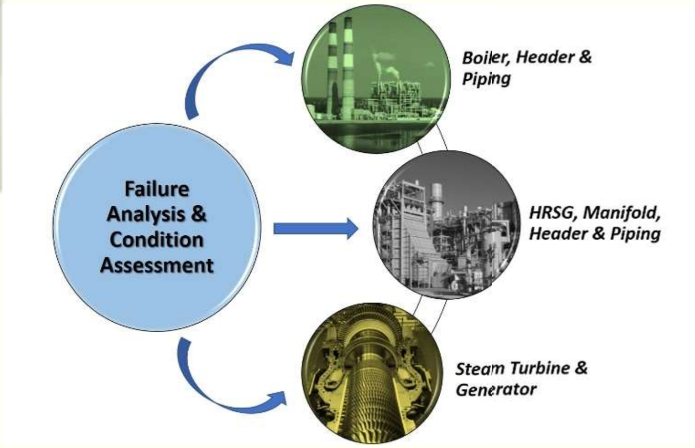

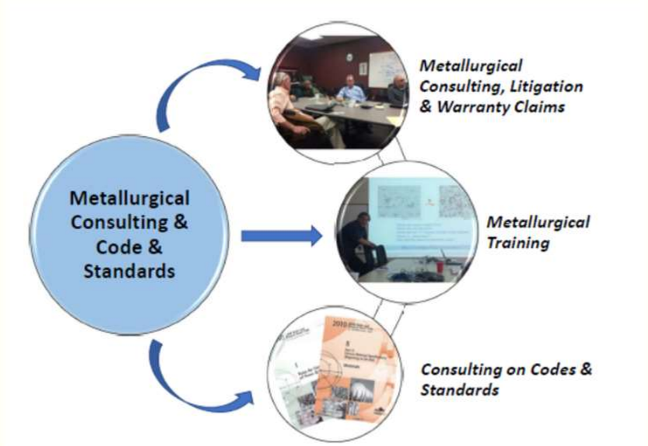

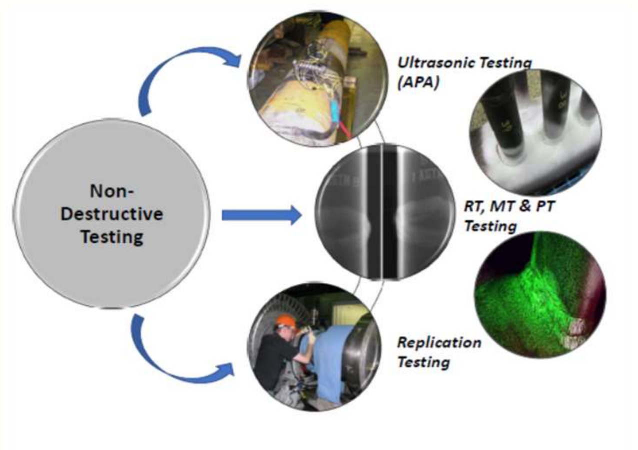

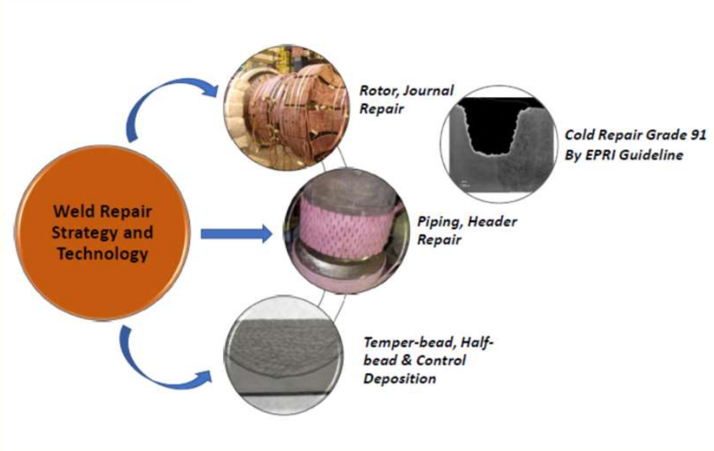

THANK YOU!

Any Questions?