Appendix 6

Control of Relaxation Cracking in austenitic high temperature components

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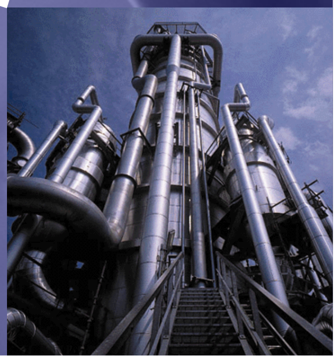
TNO Science and Industry

Presentation for EFC, WP 15:
"Corrosion in Refinery"
April 26th, Paris



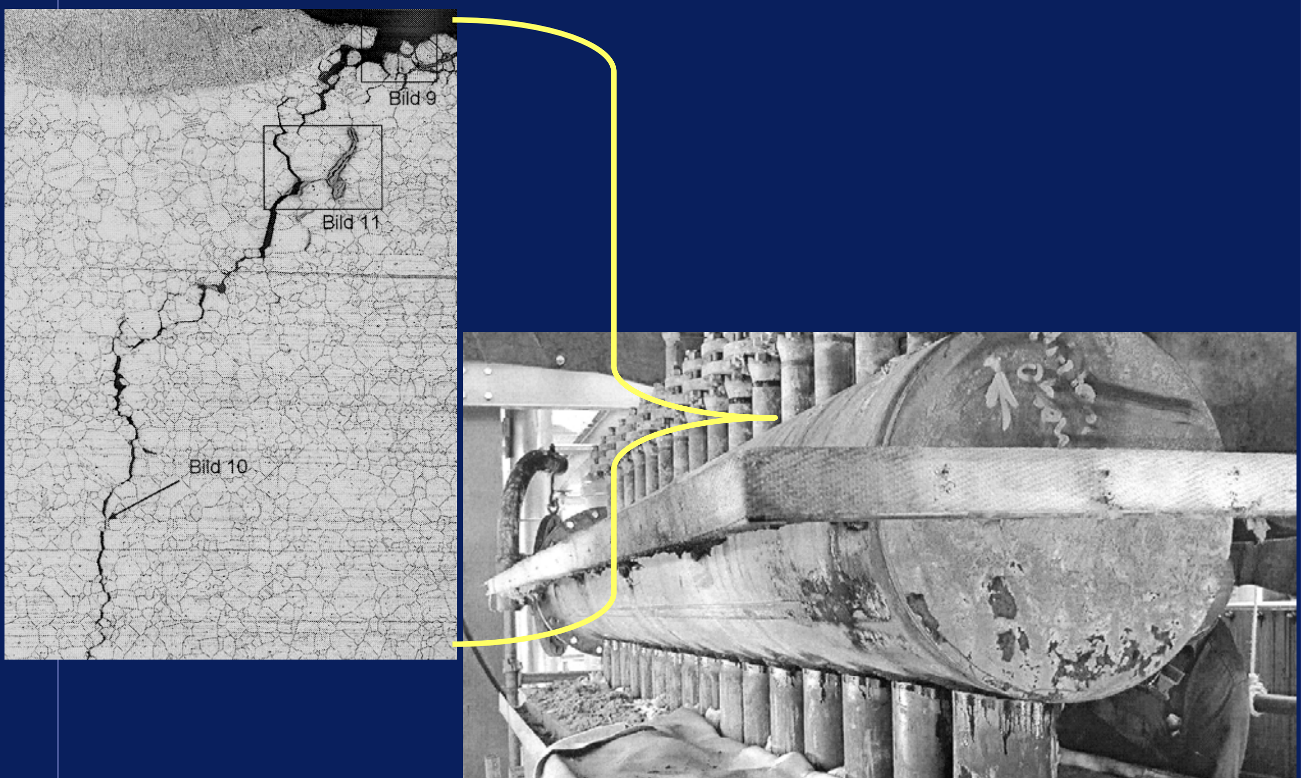
Hans van Wortel,
Eindhoven
The Netherlands

DIFFERENT NAMES FOR THE SAME DEGRADATION MECHANISM IN AUSTENITIC MATERIALS?

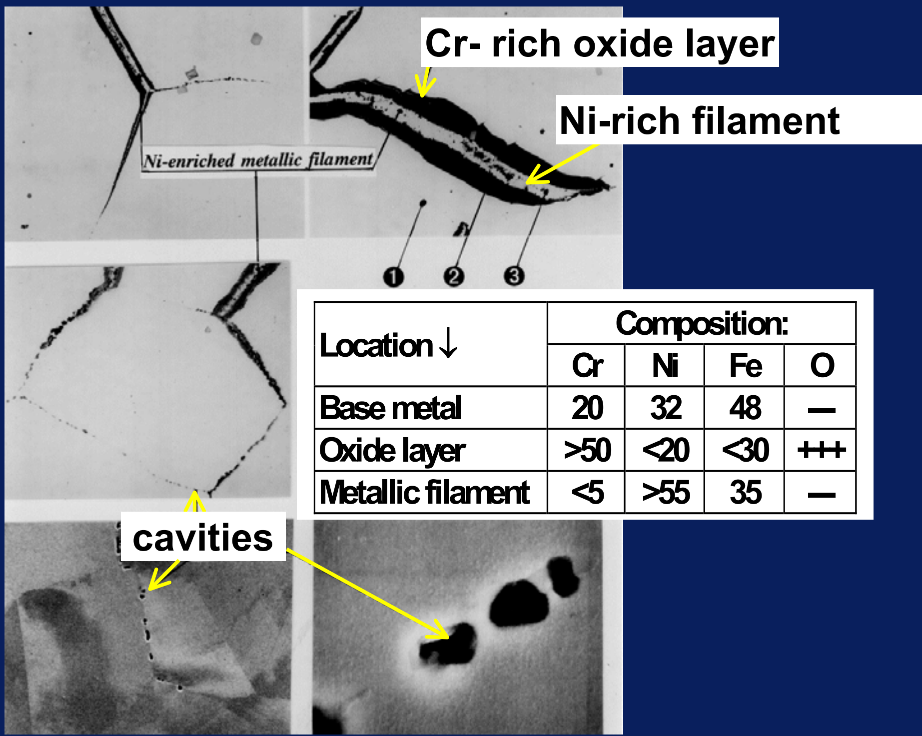
• Relaxation Cracking	RC
• Stress Induced Cracking	SIC
• Stress Induced Corrosion Cracking	SICC
• ReHeat Cracking	RHC
• Stress Oxidation Cracking	SOC
• Stress Assisted Grain Boundary Oxidation	SAGBO
• Stress Relief Cracking	SRC
• Post Weld Heat Treatment Cracking	PWHTC
• White Phase Fractures	WPhF
• Strain Age Cracking	SAC

Failed Alloy 304H reactor vessel, wall thickness between 50 and 75 mm

Failed 800H header in the year 2005



Example of the appearance of relaxation cracks in Alloy 800H



Location↓	Composition:			
	Cr	Ni	Fe	O
Base metal	20	32	48	—
Oxide layer	>50	<20	<30	+++
Metallic filament	<5	>55	35	—

RELAXATION FAILURES IN THE CHEMICAL PROCESS INDUSTRIES

(Identified by the author)

- Germany : 800H, 16Cr13NiNb, Alloy 617, Alloy 625
- Canada : 800H(T)
- US : 800H(T), 304H, 347H, Alloy 617, 25/35Nb, 601
- Belgium : 800H, 321H, 304H, Alloy 601. Aloy 617
- Norway : 321H, 347H
- France : 800H, 347H, AISI 310, Alloy 601
- UK : 800H, 316H, 304H
- Netherlands: 800H, 304H, 316H, 321H, 20.32Nb, 617
- Asia : 800H(T), 321H, 347H, Alloy 601.
- Africa : 347H

Totally >50 failures identified during last decade

Last year: 6 new failures, 4 of them in 347H

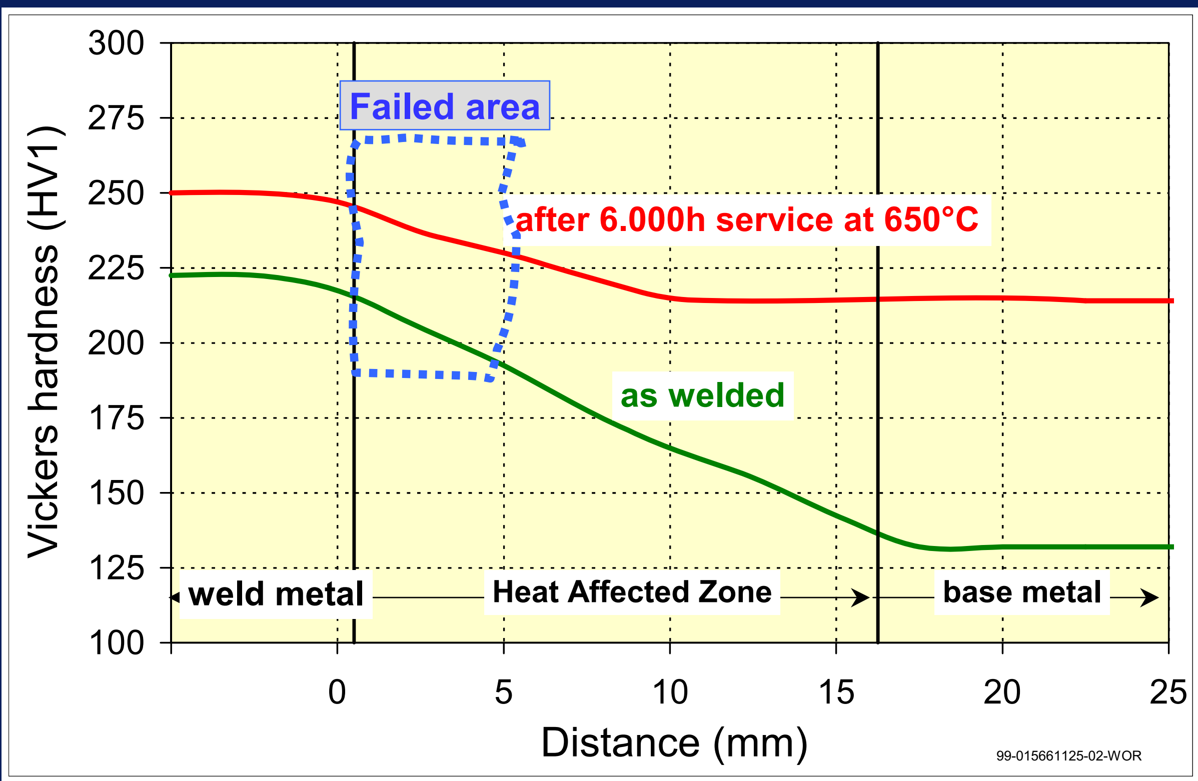
STARTING POINT JIP RESEARCH:

Case 1:

- failure in a Alloy 800H reactor vessel after 6.000h service -

- Diameter vessel : 2.800 mm
- Total height: 15 meter
- Wall thickness shell between 35 and 80 mm.
- Medium: hydro-carbons
- Metal temperature 600-650°C
- Leakage after 2.000h in the 80 mm material
- After 6.000h a catastrophic failure. Brittle fracture in HAZ of circumferential weld. Vessel broke in 2 parts resulting in a fire. However, no persons were killed

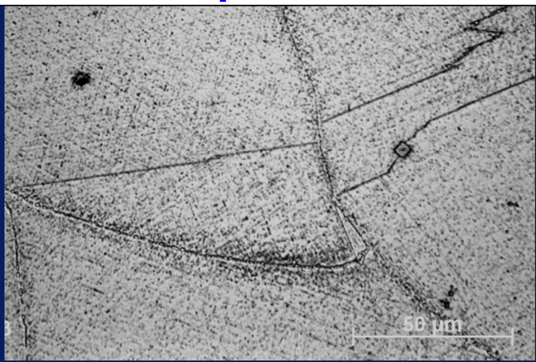
Hardness and failed area of a Alloy 800H welded joint



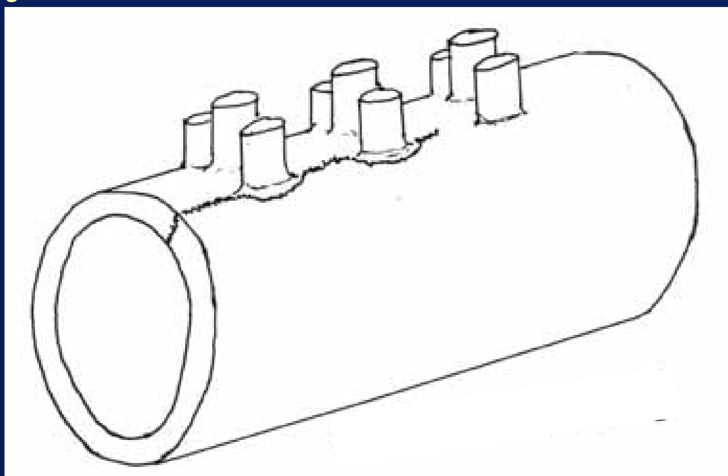
Microstructure failed Alloy 800H base metal/HAZ

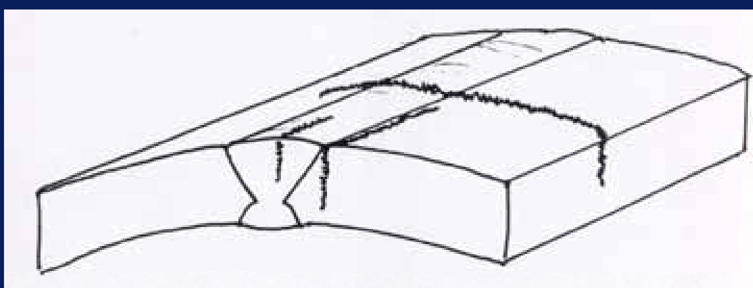
As delivered: hardly precipitates

Service exposed at 600-650°C: many very fine carbides



Detail of the failure locations of a Alloy 800H header after 12.000h service



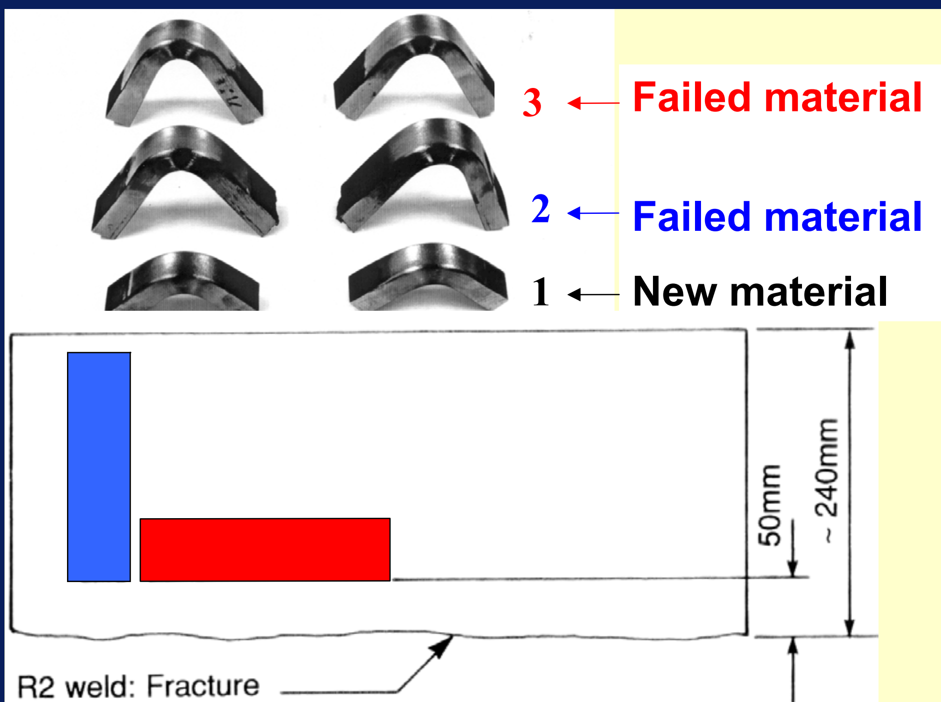


Mechanical properties of the ***2 brittle failed*** 800H components

- within requirements for new base metal ! -

Condition	$R_{0.2}$ MPa	RM MPa	A %	Z %	Toughness Joules
Required for new base metal	*≥ 170*	*450 700*	*≥ 30*	*--*	*≥ 40*
new base metal 1	195	545	53	65	235
new base metal 2	215	585	48	62	208
failed base metal 1	285	625	35	44	115
failed base metal 2	390	705	31	38	85
Crossweld new 2	310	522	--	68	106
Failed crossweld 2	535	652	--	14	55

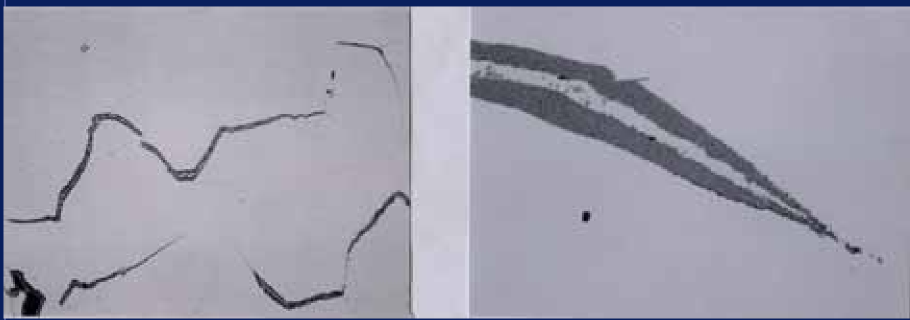
Ductile bend behaviour of the ***brittle failed*** Alloy 800H reactor vessel!



Result self restraint test of a Alloy 800H weld

Conditions heat cycle:

- heating rate 50°C/h
- aged 100h/650°C
- cooled down in furnace



Outcome:

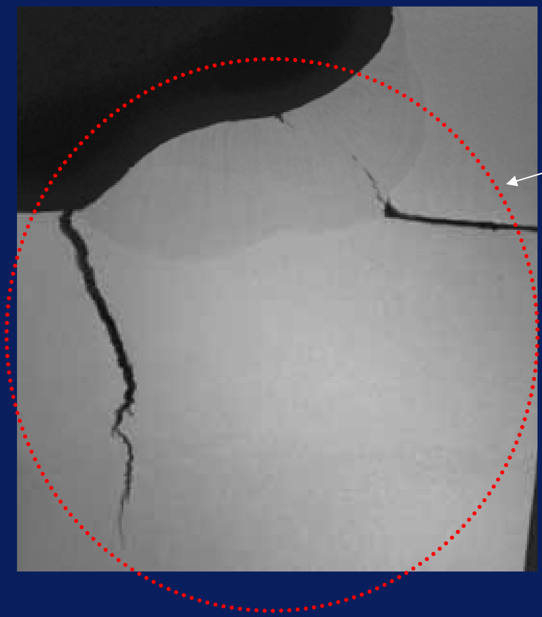
Severe relaxation cracking due to welding stresses only!

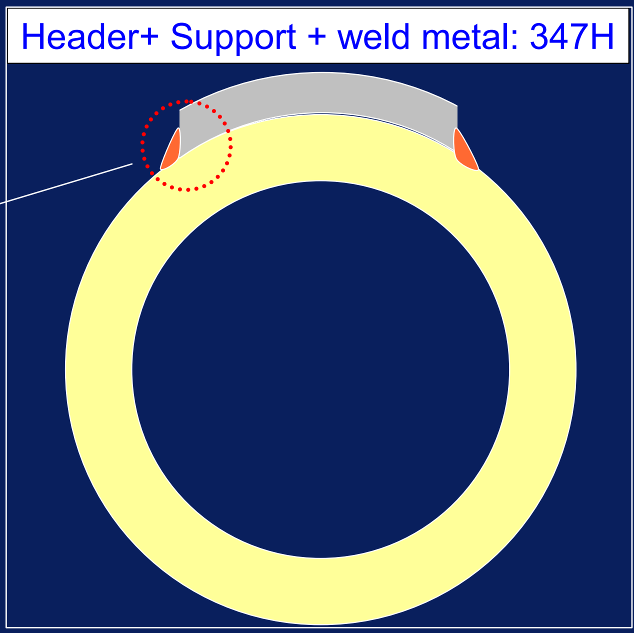
Outcome failure analysis:

- Relaxation cracking susceptibility can not be assessed or predicted with the standard mechanical tests:
  - Room Temperature: Tensile, Charpy-V and bend tests do not indicate susceptibility
  - Service temperature: Creep and L.C.F tests do not give information concerning susceptibility

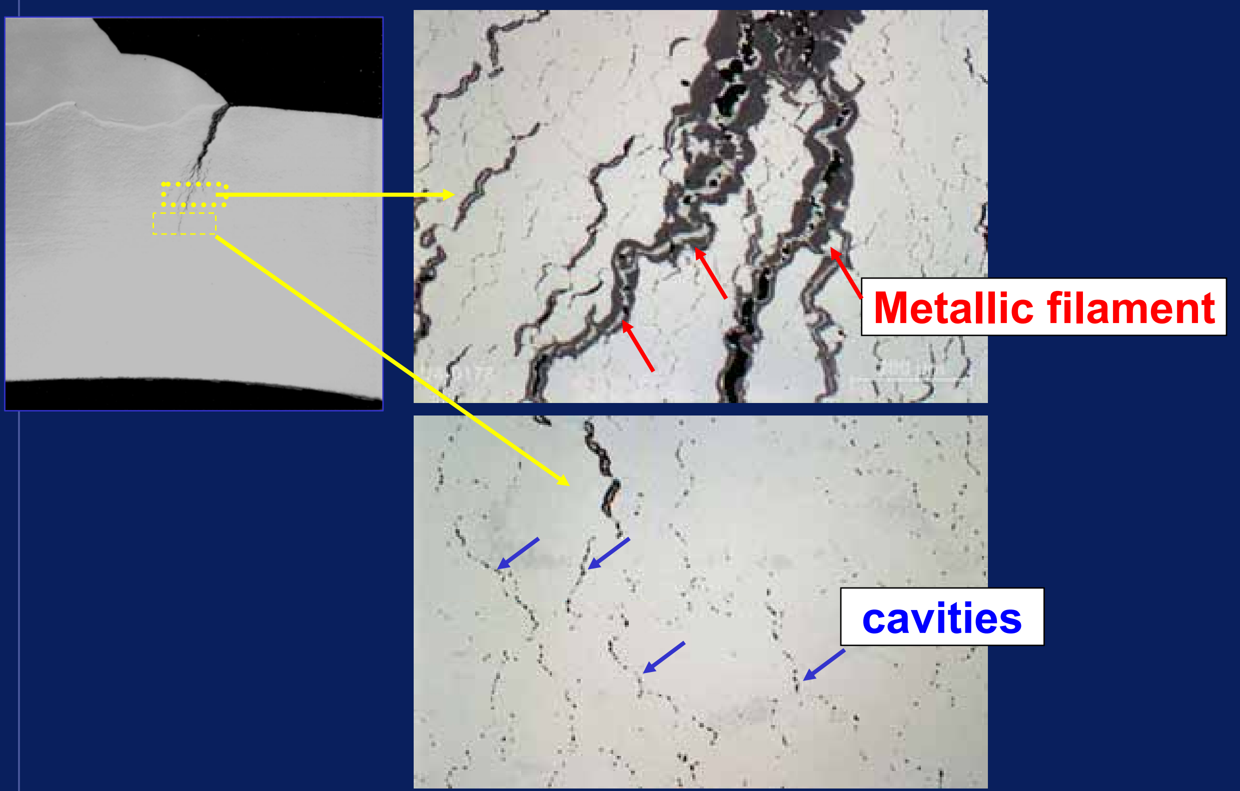
CONCLUSION:
Within the present codes the degradation mechanism: *"Relaxation Cracking"* is not tackled

Failure in a 347H header after < 1 year service



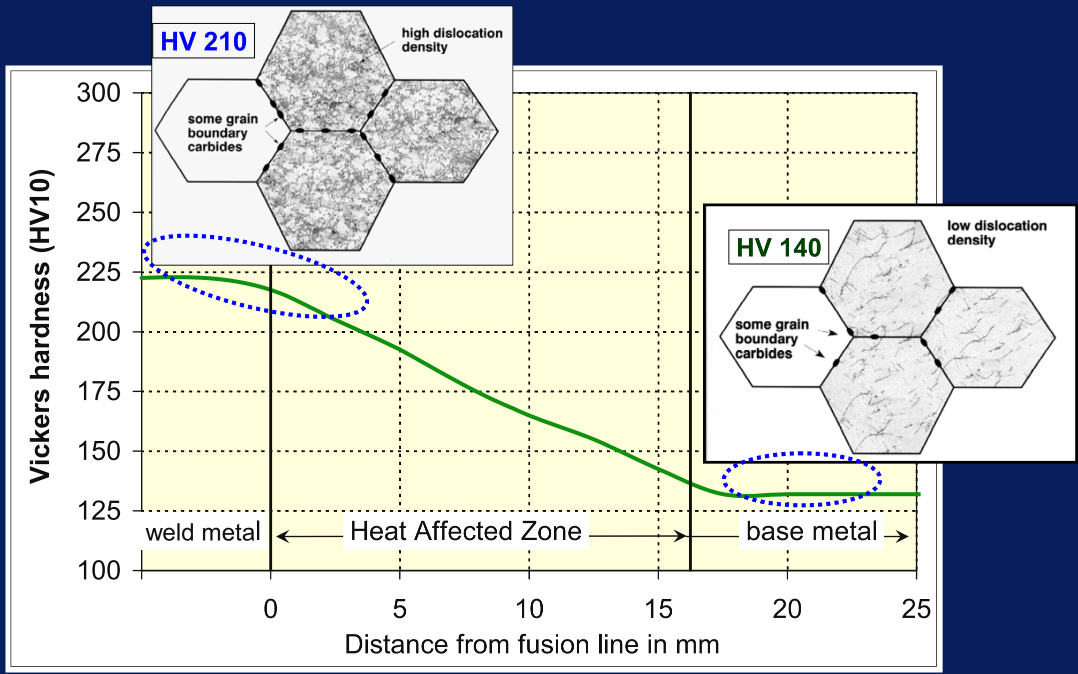


Failed 347H welded joint, cracks in HAZ/BM

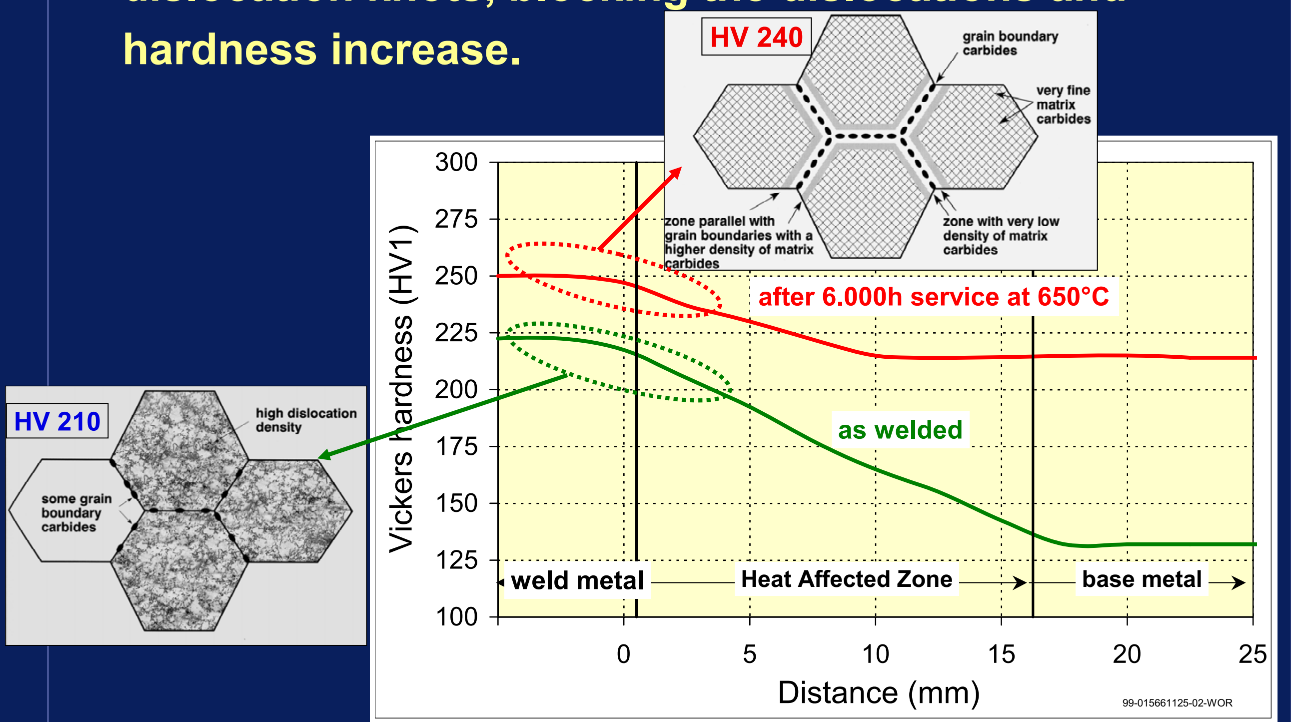


EFFECT WELDING AND COLD DEFORMATION ON RELAXATION BEHAVIOUR

- Welding/cold deformation enhance dislocation density and results in hardness increase

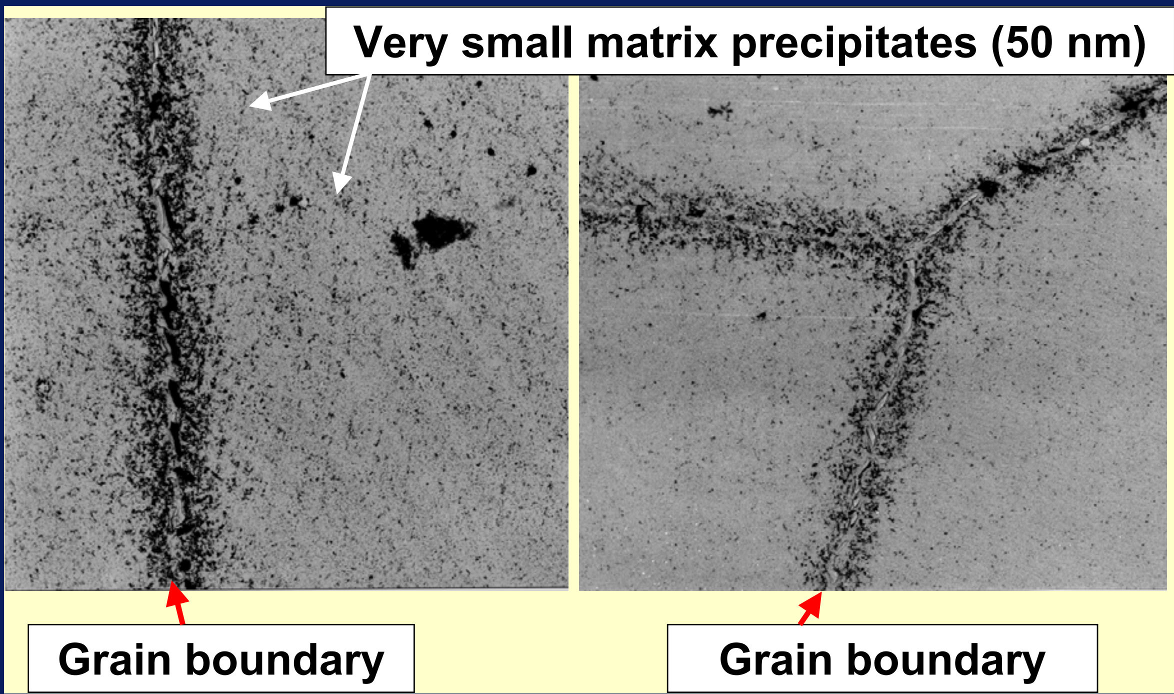


- During service this will result in:
  1. Rapid precipitation of very fine matrix carbides on dislocation knots, blocking the dislocations and hardness increase.



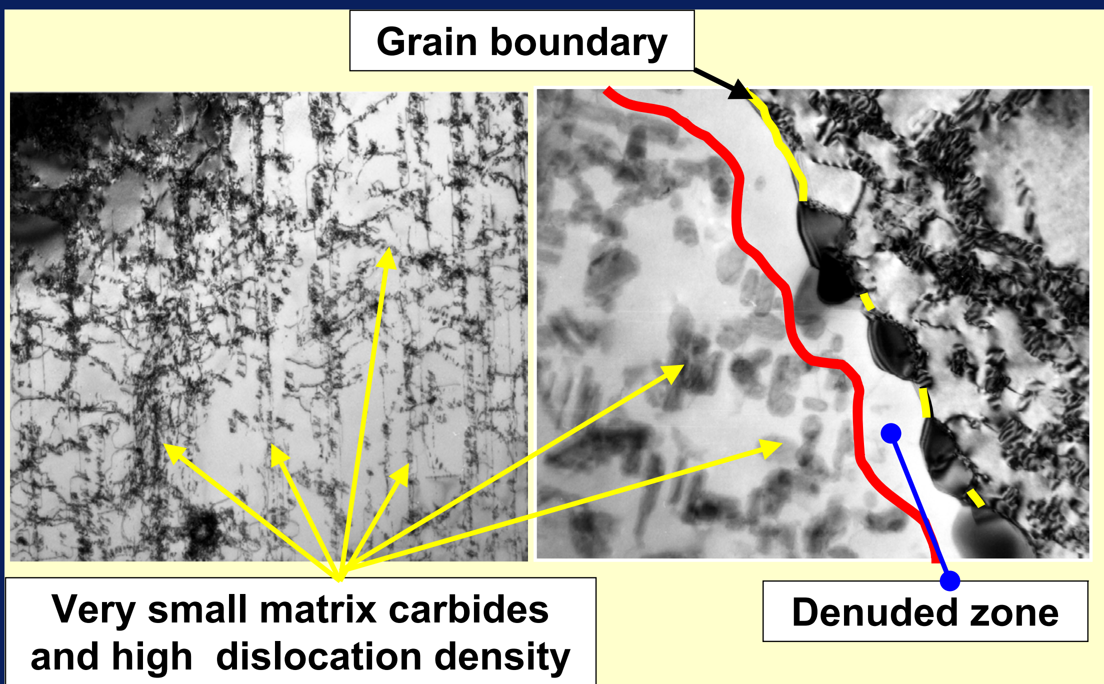
TEM extraction replica's of the failed service exposed 800H material

- matrix precipitates have been identified as $M_{23}C_6$



TEM thin foils of the failed service exposed 800H material

- many fine $M_{23}C_6$ carbides in the matrix -



Relaxation cracking in austenitic materials
- window of the degradation mechanism -

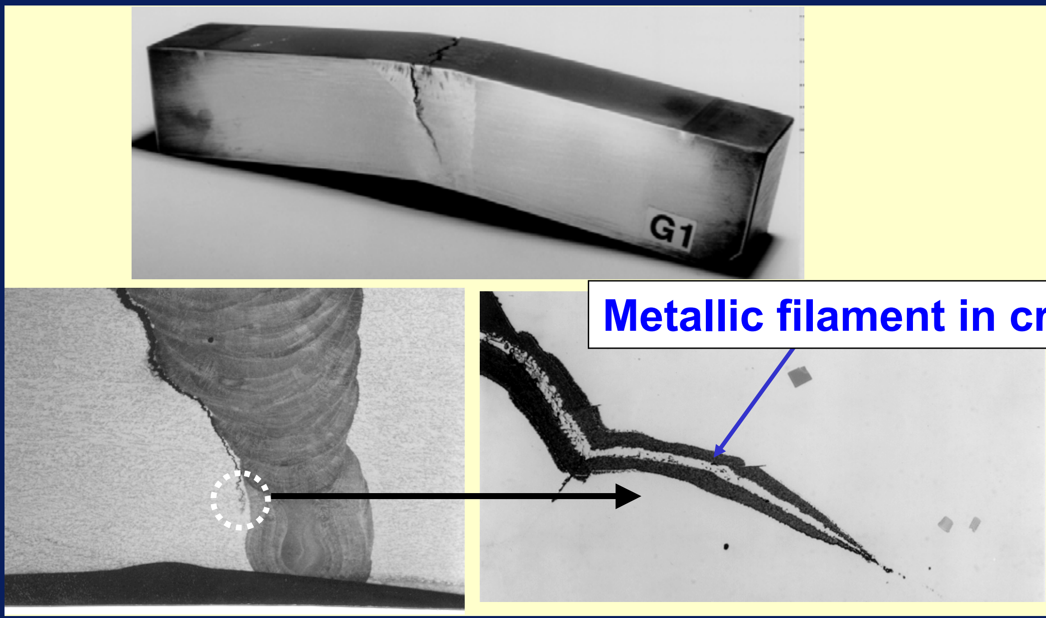
- In materials showing an age hardening behaviour:
  - Precipitation of very fine carbides (50 nm) within the grains;
  - Operating temperatures between 500 and 750°C, material dependent;
  - Susceptibility significantly enhanced by a high dislocation density, introduced by welding, cold forming, cyclic loading.

Identification of Relaxation Failures

- Cracks always on grain boundaries, often with a metallic filament;
- Cracks in (repair) welded and cold formed areas;
- In front of cracks: cavities on grain boundaries;
- Vickers hardness > 200 HV5;
- Within 0.5 - 2 years service;
- Metal temperature between 500 and 750°C.

Relaxation Cracks can be simulated in the lab

- result of a relaxation test on a Alloy 800H welded joint -



Temperature: 600°C. Testing time: 150h.

Launch of a Joint Industrial Programme:
- Control of Relaxation Cracking -

Consortium:

* Shell	* Exxon	* Stoomwezen	* Total	* GEP
* Dow	* BASF	* Norsk Hydro	* DSM	* Nuclear Electric
* BP	* Siemens	* Air Products	* Kema	* Laborelec
* VDM	* Manoir	* Haynes	* DMV	* Special metals
* TNO	* Paralloy	* UTP	* Thyssen	* Böhler
* ABB	* Technip	* Uhde	* Raytheon	* Industeel
* AKF	* Stork	* Verolme	* Bodycote	* Schielab

Objectives JIP:

- What are the determine factors concerning relaxation failures in austenitic materials?
- How to control the phenomenon ?

Extent of the programme

- Assess the effect of:
  - Chemical composition base materials (both Fe and Ni base). >20 base materials involved.
  - Heat to heat variation.
  - Grain size.
  - Welding and type of consumables (> 60 conditions).
  - Cold deformation.
  - Operating temperature.
  - Pre- and Postweld / Postform heat treatments.

Reference materials: Alloy 800H and Alloy 617

AISI 347 was not included in the programme

Effect of material choice

- some base materials involved and their susceptibility for RC -

Base metal:	C	Ni	Cr	Fe	Al	Ti	Mo	Co	others
304H	.06	10	17	bal.	---	---	---	----	
316H	.07	11	17	bal.	---	---	2.5	---	
321H	.07	11	18	bal.	---	0.4	---	---	
1.4910	.03	13	17	bal.	---	---	2.4	---	N, B
NF 709	.08	25	20	bal.	---	0.1	1.5	---	N, B, Nb
Alloy 800H	.07	32	20	bal.	0.3	0.3	---	---	
Alloy 803	.08	34	25	bal.	0.5	0.5	---	---	Nb
AC66	.06	32	27	bal.	---	---	---	---	Nb, Ce
602CA	.17	63	25	9	2.1	.18			
Alloy 617	.07	bal.	21	<2	0.9	0.4	9	12	

Effect of welding and consumable selection

- some results in as welded condition -

- **Mostly the welded joints are more susceptible than the base materials.**

- ***Not susceptible base metal:***
  - AC66 → WM not susceptible
  - Alloy 800 → WM is susceptible
  - Alloy 803 → WM is susceptible
  - 1.4910 → WM not susceptible

- ***Weldment, no PWHT:***
  - WM not susceptible
  - WM is susceptible
  - WM is susceptible
  - WM not susceptible

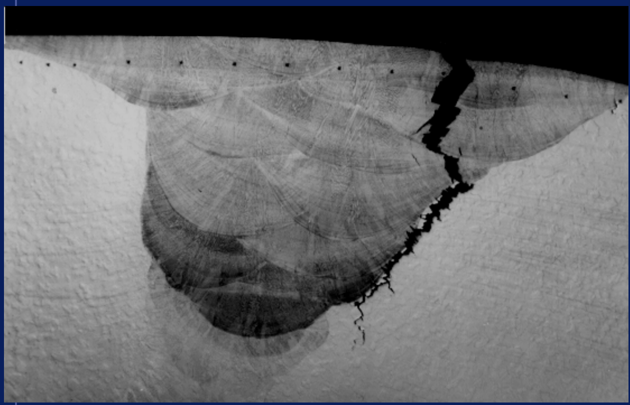
SOME FACTS

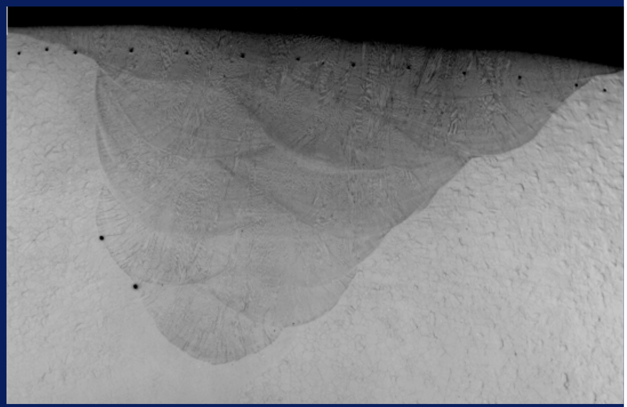
- In age hardened condition relaxation cracks can be expected at <0.2% relaxation strain.
- Welding and some cold deformation (<2%) can already produce these low relaxation strains during high temperature service.
- After additional heat treatments the components can withstand >2% relaxation strain without cracking. *This is far beyond the relaxation strains in the field.*

Effect of heat treatments

- Stabilising heat treatment base materials:
  - Effective to avoid Relaxation Cracking, both in as delivered condition as after cold forming
- Postweld heat treatments welded joints:
  - Effective to avoid Relaxation Cracking in the welds

Effect PWHT on relaxation cracking susceptibility of a Alloy 617 welded joint



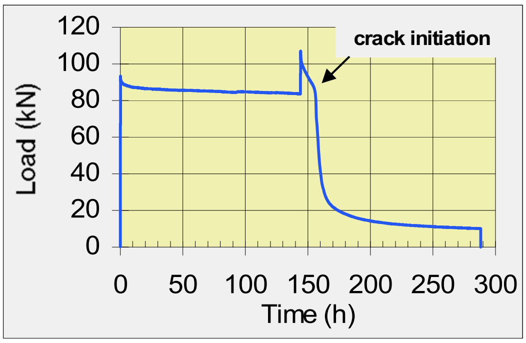


As welded:
cracked in WM+HAZ

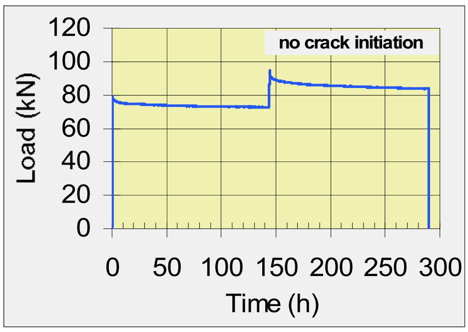
After PWHT at 980°C:
no RC cracks

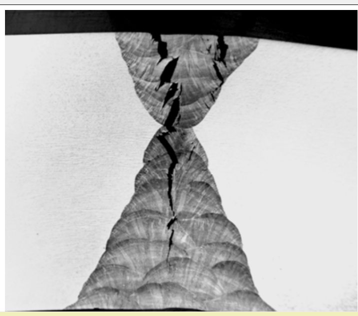
Effect heat treatment on relaxation performance weld
- welded joint is after heat treatment not susceptible for RC -

As welded condition, T=650°C

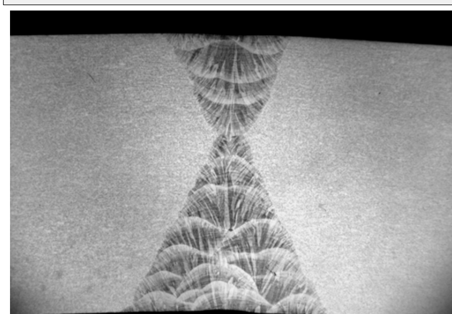


Weld stabilised (980°C/3hr), T=650°C





Severe cracking in weld metal



No damage at all

Deliverables Joint Industrial Programme

- Recommended Practice for the identification and prevention of Relaxation Cracking
- Equipment Degradation Document (EDD)

The control of the degradation mechanism "RELAXATION CRACKING"

- Implementation results in the field and outcome -

- Companies within the JIP consortium do not have failures anymore for > 4 years. They all are using the Recommended Practice (mostly heat treatments).
- Still failures are encountered at companies who were not involved in the programme.

General final conclusion

- To date Relaxation Cracking is under control by a correct selection of:
  - base materials
  - welding consumables
  - heat treatments
  - Equipment manufacturer

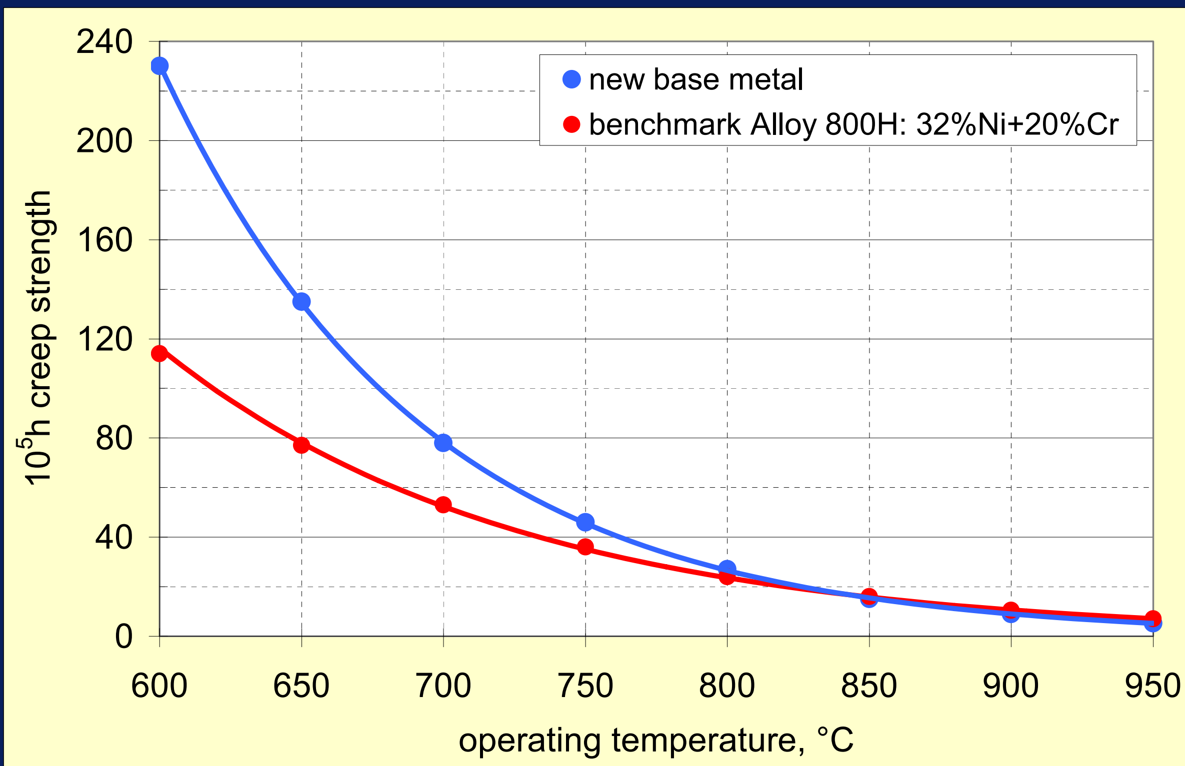
OUTLOOK

- A material has been developed:
  - Not susceptible for relaxation cracking, where a PWHT can be avoided with:
    - A high creep strength
    - For operating temperatures from 600 up to 950°C
    - Cost effective where the Ni content is significantly lower than for Alloy 800H

New developed cost effective base material not susceptible for relaxation cracking between 600 and 700°C

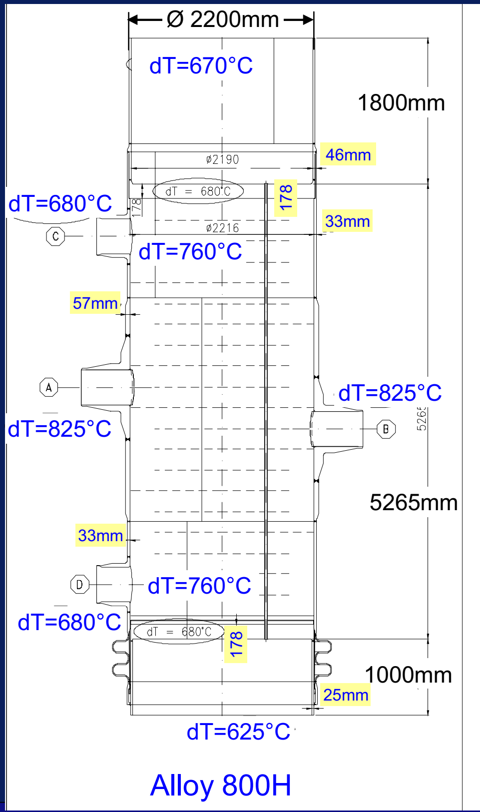
Test conditions:	Base metal 20 mm:			Base metal 40 mm:		
Test temperature, °C	600	650	700	600	650	700
Relaxation time, h	288h	288h	288h	312h	288h	288h
Relaxation strain, %	0.40	1.2	4.3	0.4	1.1	3.1
Damage class:	**0**	**0**	**0**	**0**	**0**	**0**
Damage class:	0 = no damage: not susceptible for RC 2 = micro cracks+cavities: susceptible for RC 3 = macro+micro cracks: very susceptible for RC					

10^5h creep rupture strength new developed base material, not susceptible for relaxation cracking compared to 800H



Cost effectiveness new base material not susceptible for relaxation cracking

- Based on a Alloy 800H heat exchanger,
  - **Weight 86 tonnes**
  - **Diameter 2.2 meter**
  - **Height 8 meter**
  - **Shell thickness from 25 up to 57 mm**
  - **2 tube sheets, 178 mm each**
  - **Several forgings**
  - **A number of tubing**
  - **Design temperature between 625 and 825°C**



Calculations performed by an equipment manufacturer

Cost item	Relative cost Alloy 800H	Relative cost new material	Cost benefit new material relative to Alloy 800H
Material	100 %	69 %	31 %
Labour	100 %	98 %	2 %
Various	100 %	90 %	10 %
Total	100 %	75 %	25 %