Dissimilar Metal Weld (DMW) Process
RAI 88, Supplement 1 (Q 05.02.03-10)

AREVA NP Inc. and the NRC
June 25, 2009

Introduction

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Lead Licensing Engineer
New Plants Regulatory Affairs

Agenda

- Objectives (R. Wells)
- Background (R. Wells)
- Improved Design of Dissimilar Metal Welds (DMW) and (P. Joly)
  - Evolution of the Design of DMWs (A. Peigney)
  - New DMW Welding Design
  - Metallurgical and Mechanical Characterization
  - Effect of PWHT on Safe Ends
- Conclusions (P. Joly)

Meeting Objectives

- Describe the DMW process for the U.S EPRTM.
- Resolve NRC questions regarding the narrow groove welding of nozzle to safe ends without first applying a buttering layer.
- Discuss the post weld heat treatment (PWHT) procedures used in welding procedure qualification testing and those proposed to be used during fabrication.
- Discuss RAI status and path forward.

Background

> **RAI 88, Question 05.02.03-10:**
> **FSAR Sections 5.3 and 3.6.3 indicate that dissimilar metal welds (DMWs) joining low alloy steel nozzles and stainless steel safe ends will use the GTAW process with a narrow groove weld joint design and no weld buttering of low alloy steel nozzles. The staff requests the following information in order for the staff to complete its review.**

1. **Discuss development and testing programs that AREVA has performed on narrow groove welding of nozzle to safe ends without first applying a buttering layer.**
2. **Discuss the PWHT procedures used in welding procedure qualification testing and those proposed to be used during fabrication. In addition, discuss any nontraditional PWHT regimes and discuss their adequacy.**
3. **Discuss typical HAZ impact test values (Charpy and mills lateral expansion) obtained during welding procedure qualification and discuss controls on welding to ensure that production welds will have similar fracture toughness to the fracture toughness testing results from welding procedure qualifications.**
4. **Discuss welding process controls employed to reduce weld metal dilution in order to retain the maximum percentage of Chromium possible in order to decrease the susceptibility of components to stress corrosion cracking for the life of the plant.**

Background

> **Response to RAI 88, Question 05.02.03-10:**

1. **Based on experience, AREVA has developed a process which improves microstructure to enhance the mechanical properties at the interface, reduces the risk of cold cracking due to the martensitic layer at the fusion line of the buttering, and reduces the risk of intergranular corrosion sensitization of the austenitic SS first layer due to carbon diffusion.**
   To improve the weld, AREVA developed an Alloy 82 DMW in which the buttering was performed by hot wire gas tungsten arc welding (GTAW) with Alloy 82, the weld used Alloy 82, and the DMW was given a post-weld heat treatment (PWHT). This process improved the weld solution since there was no martensitic microstructure potentially sensitive to hydrogen cold-cracking, and the mechanical properties also significantly increased compared to the previous process.
   AREVA NP has gained experience with GTAW narrow gap welding of stainless steel primary piping and developed a narrow gap welding process for DMW. AREVA NP has improved the welding procedure by achieving, in a narrow groove, a one-pass-per-layer weld totally comprised of Alloy 52. The microstructure and properties of this type of DMW were studied on several full scale mock ups, as a function of the PWHT. A detailed description of the microstructure close to the fusion line was collected along with the influence of the PWHT; extensive mechanical testing was also performed at the interface. The mechanical testing results showed that the Charpy impact toughness depends on the position of the notch. Even when the crack tip is located in the lowest Charpy toughness zone, the equivalent reference temperature for the nil ductility transition (RTNDT) deduced from fracture toughness tests is below the specified RTNDT of the neighboring low alloy ferritic material.
   Alloy 52 is resistant to primary water stress corrosion cracking (PWSCC). Additionally, tests were performed to demonstrate the resistance to PWSCC of the interface between Alloy 52 and the 308L cladding of the low alloy steel. Corrosion tests, including very severe reverse U-bend (RUB) tests in primary water at 680°F, which sampled the weld metal itself and the interface with 308L, did not show crack initiation after 10,000 hours. The tests demonstrated the metallurgical quality of the GTAW narrow gap Alloy 52 DMW.

Background

> **Response to RAI 88, Question 05.02.03-10 (cont'd):**

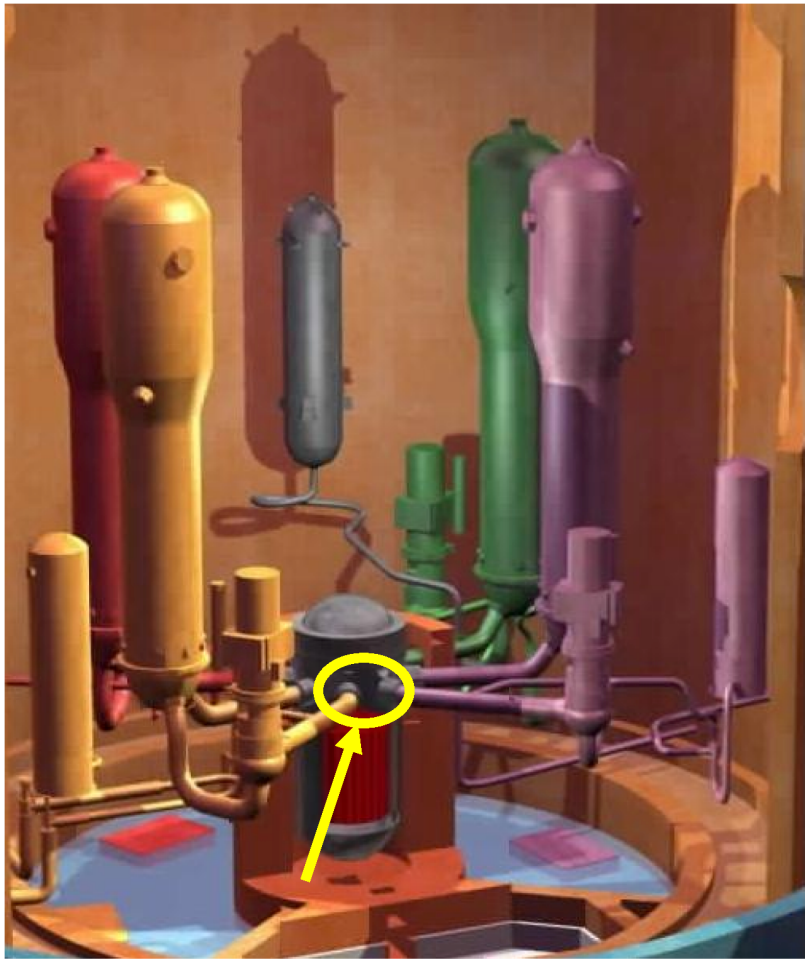
2. **The results of a weld development study for the U.S. EPR dissimilar metal welds will be available later in the design process. The PWHT procedure used for the welding qualification will be representative of the procedure used for manufacturing. It is not intended to employ any nontraditional heat treatment regimes.**
3. **The results of a weld development study for the U.S. EPR dissimilar metal welds will be available later in the design process. Procedure qualifications and weld procedures are not yet developed; therefore, HAZ impact test values will be available later in the design process.**
4. **Welding procedures will be developed for U.S. EPR dissimilar metal welds later in the design process. Qualification of these procedures will include consideration of weld metal dilution level and the maximum percentage of residual acceptable chromium.**

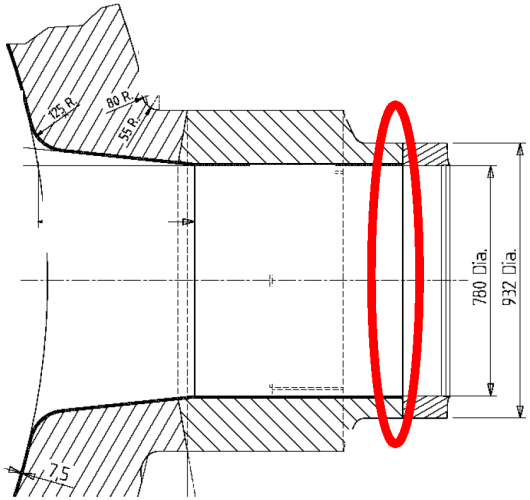
Improved Design of DMWs

Pierre Joly
Section Head-Metallurgy and Corrosion
Materials Technology and Chemistry Department

Alain Peigney
European Welding Engineer
Head of Welding Processes
Welding Department

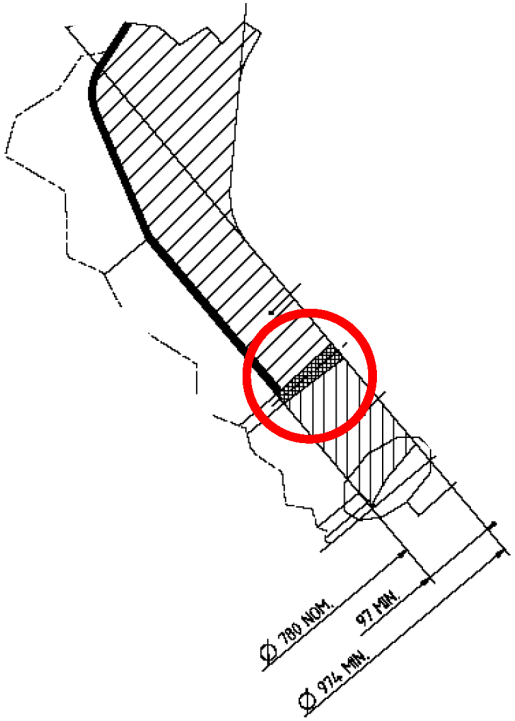
DMW Location and Geometry





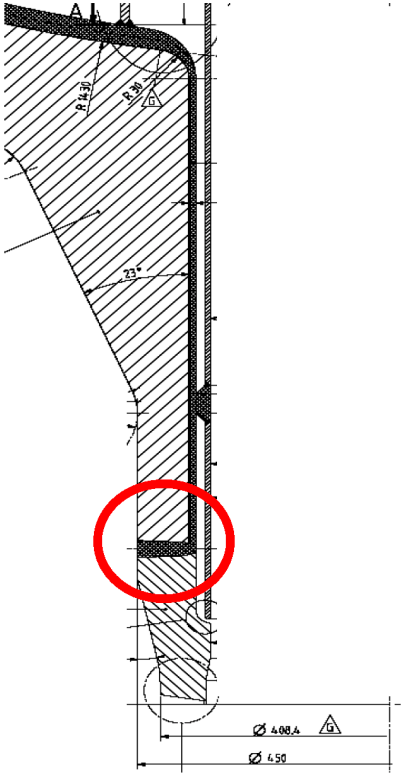
> **Reactor pressure vessel (RPV) nozzles:**
  - **In. Diameter 30 in.**
  - **Thickness 3 in.**

DMW Location and Geometry (cont'd)



> **Steam generator nozzles:**
- **In. Diameter 30 in.**
- **Thickness 3.7 in.**

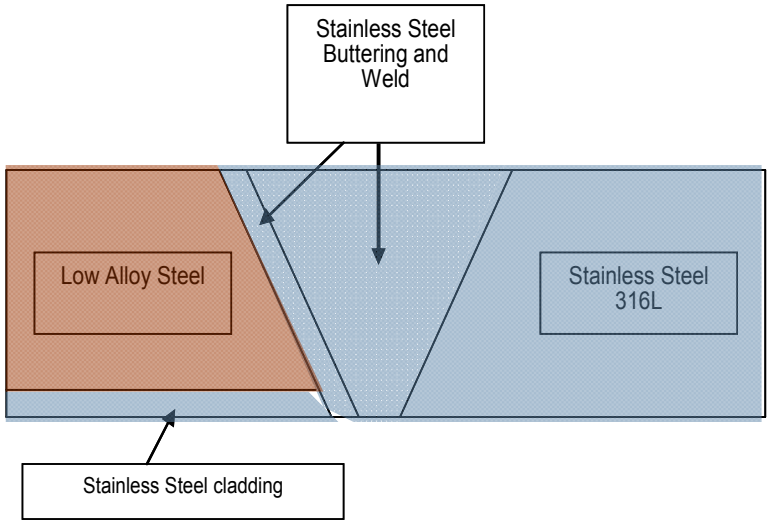
DMW Location and Geometry (cont'd)

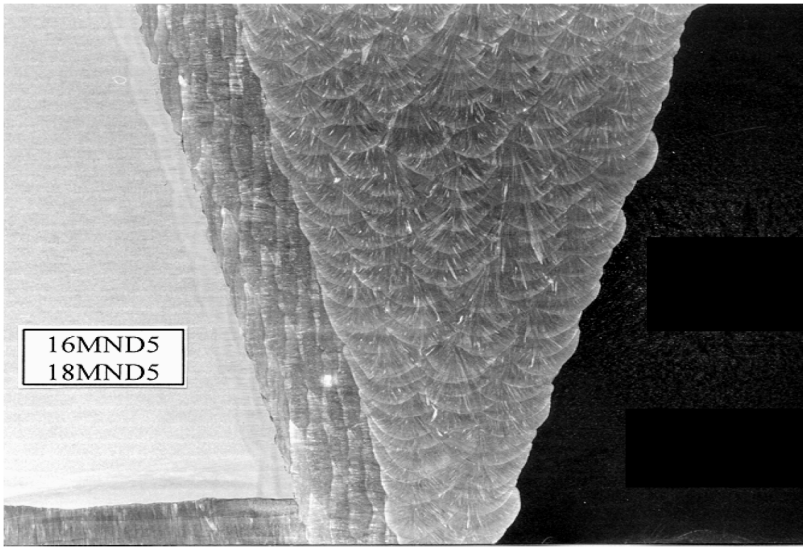


> **Pressurizer nozzles (e.g., surge line):**
  - **Diameter 14 in.**
  - **Thickness 1.8 in.**

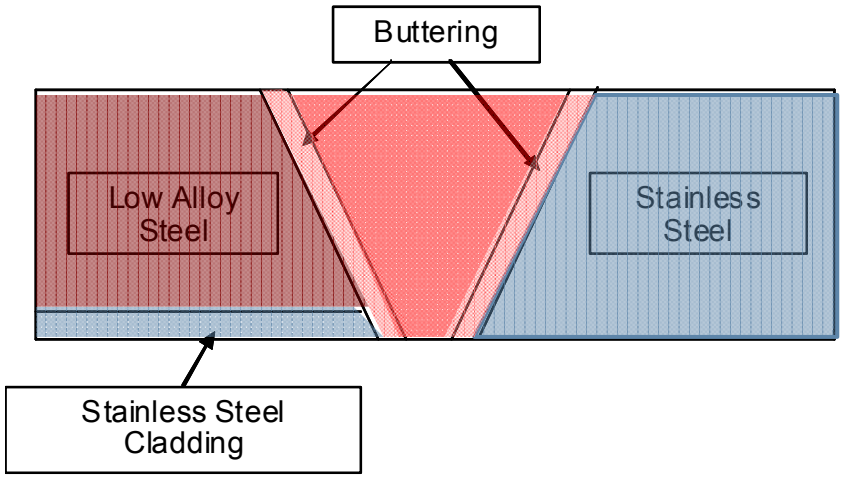
Evolution of the Design of DMWs

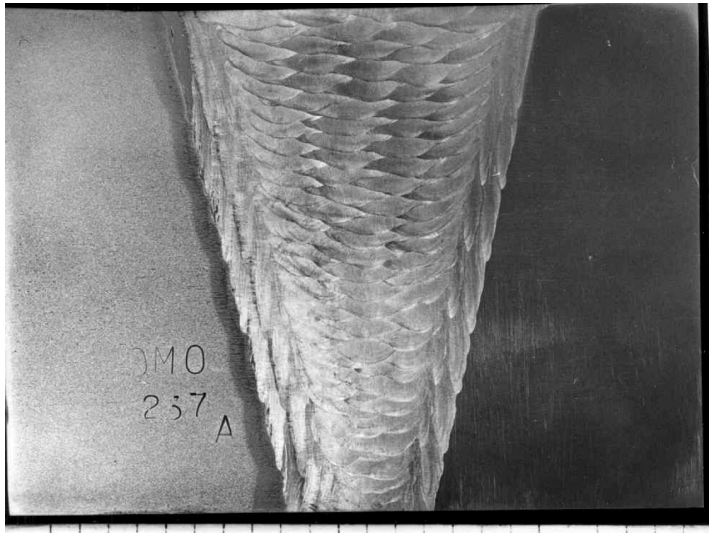
Example of DMW Old Design Stainless Steel (SS) with Butter Weld



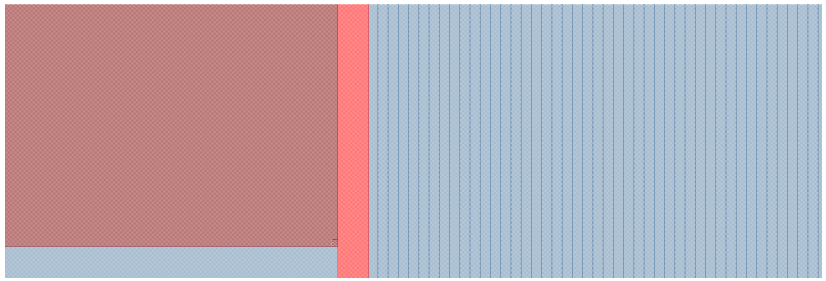


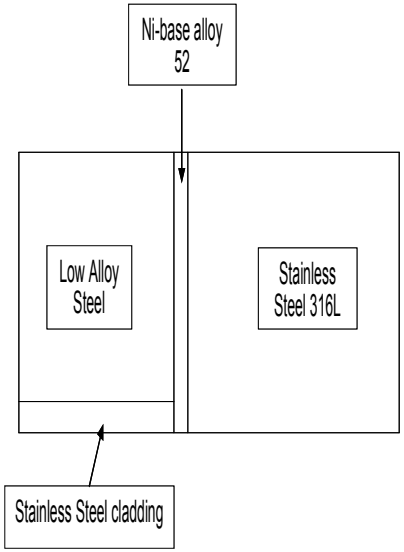
DMW Old Design
Inconel DMW with Butter Weld

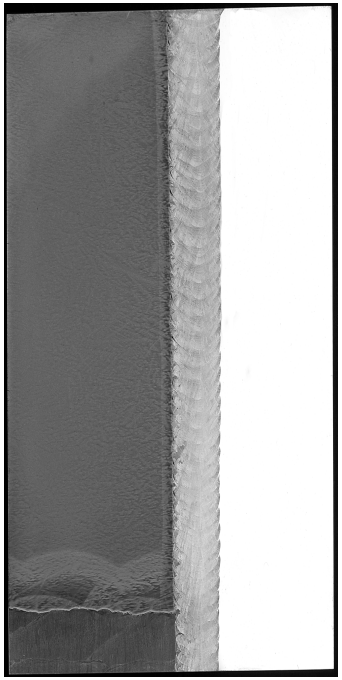




Improved DMW Design
Narrow Gap Inconel 52 DMW without Butter Weld

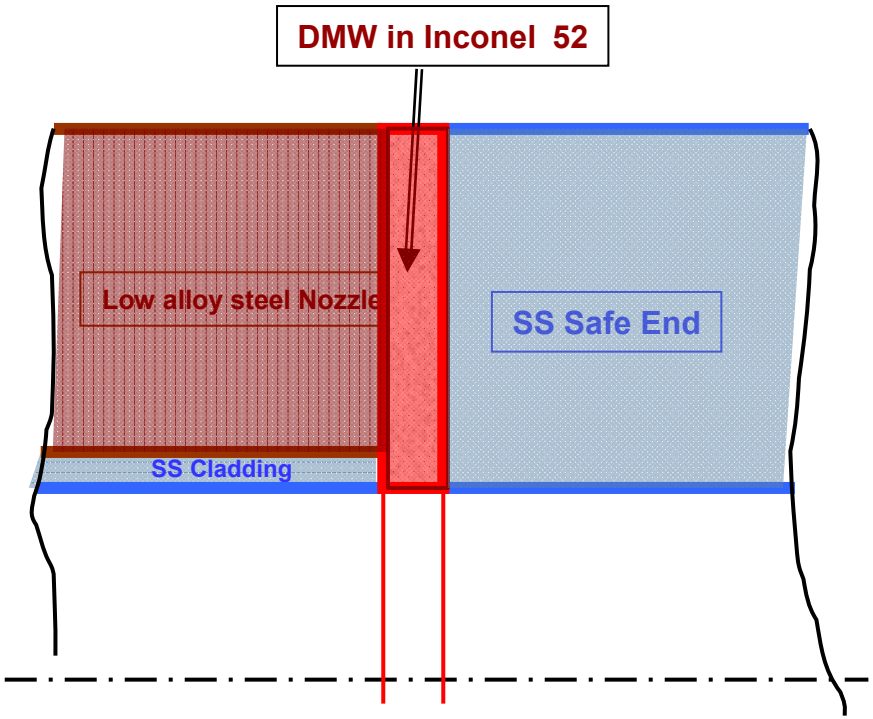






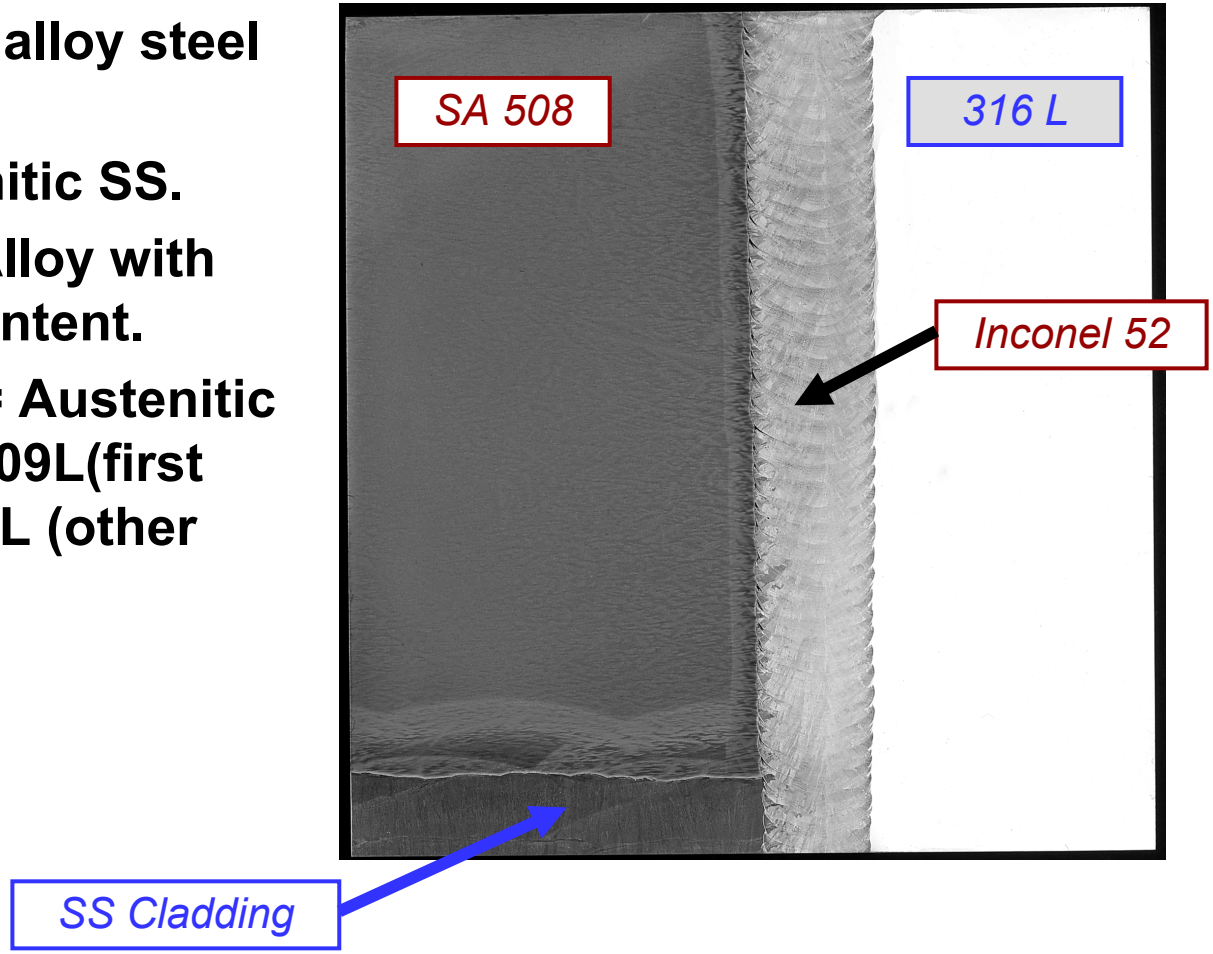
DMW New Design

- No Buttering.
  - Reduced manufacturing operations.
    - Machining.
    - Buttering and nondestructive examination (NDE).
- Automatic GTAW process.
  - Good soundness.
  - Good reproducibility.
  - Low side wall dilution.
- Narrow groove (NG) preparation.
  - Gap < 0.45 in.
  - Smaller metal deposit quantity.
  - Better geometry NDE access.
- Inconel 52 filler metal.
  - Good physical and mechanical properties.
  - Good corrosion resistance.



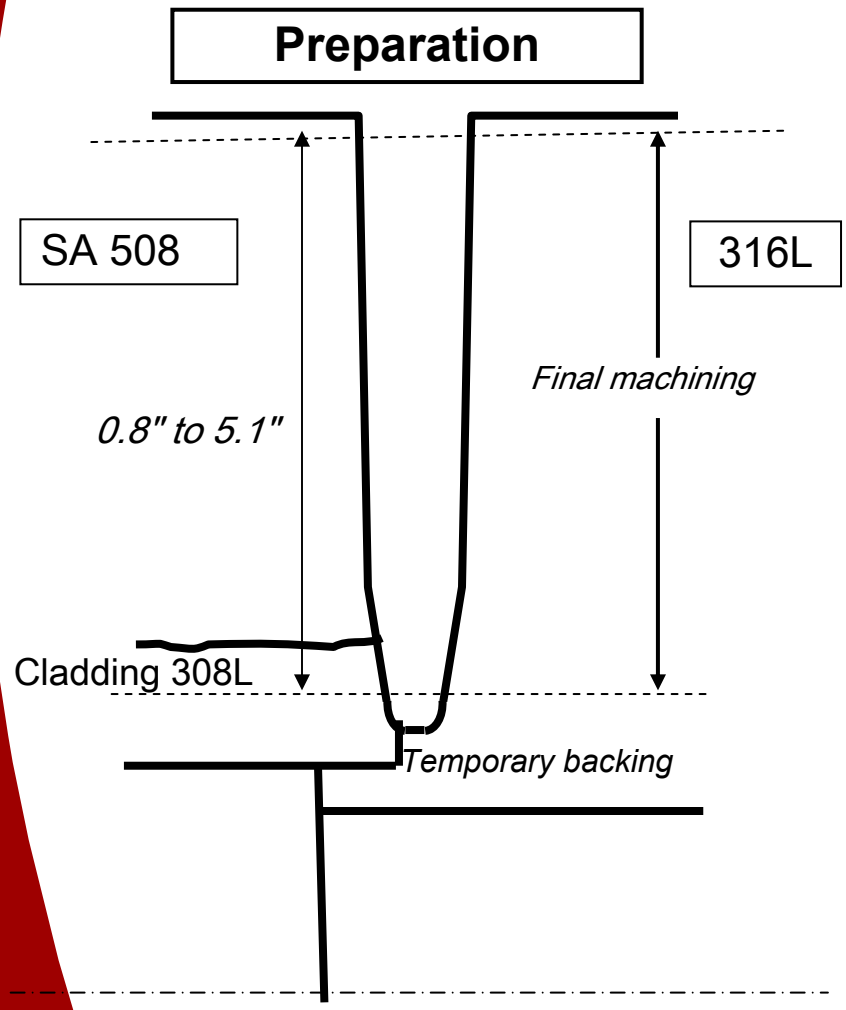
DMW New Design

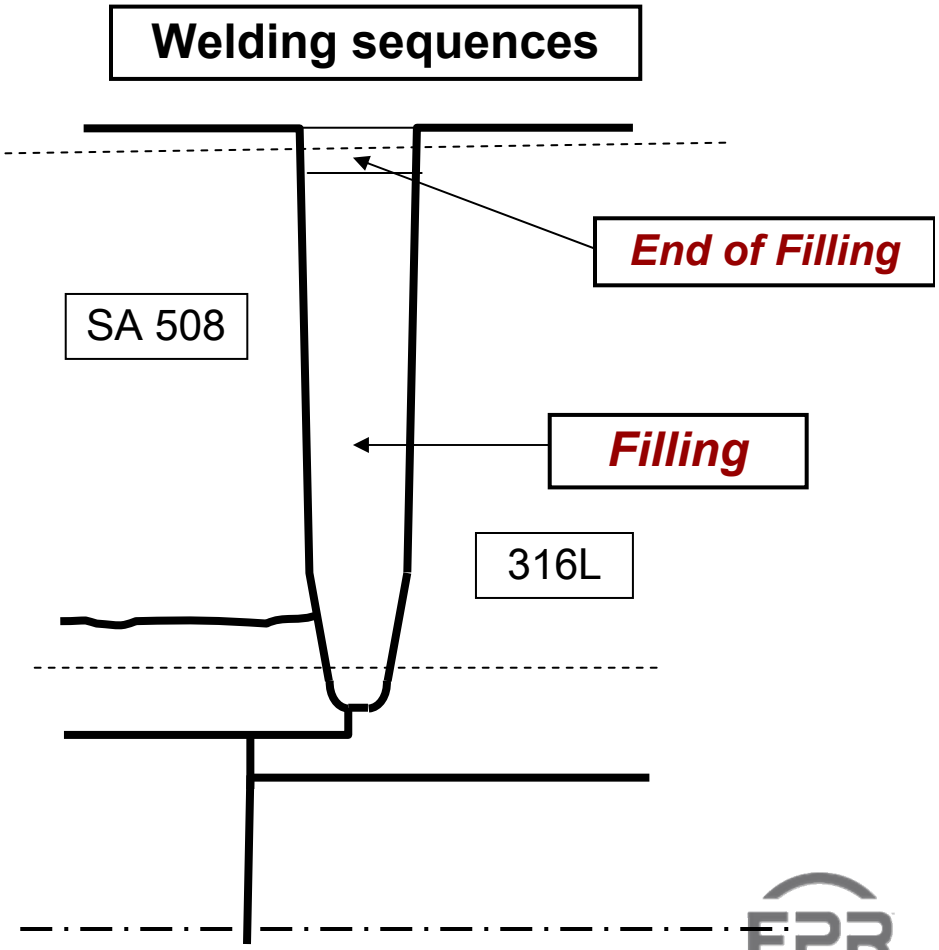
- SA 508 = Low alloy steel (Mn Ni Mo).
- 316L = Austenitic SS.
- Inconel 52 = Alloy with high nickel content.
- SS Cladding = Austenitic SS cladding 309L(first layer) and 308L (other layers).



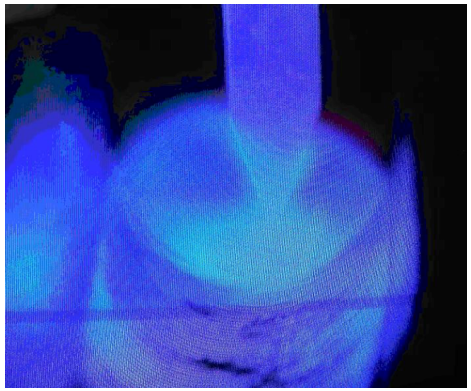
New DMW Welding Design

DMW Preparation and Welding Sequences





DMW Welding Conditions

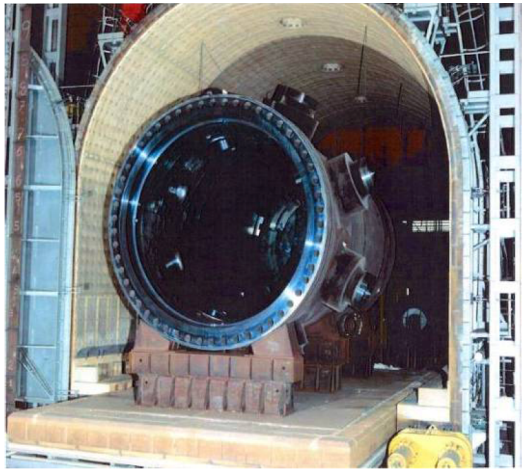


> **Keypoints:**
- Shop welding application.
- Narrow gap GTAW.
- Welding position : flat position (rotating nozzle).
- GTAW with cold wire.
  - Pulsed current.
  - Arc voltage: 12.5V (AVC using).
  - Welding speed: 3.15 in./minute.
  - Welding gas: mixture helium argon 70%-30%.
  - Heat input: 55.8 kj/in. (22 kj/cm).
- Filler metal inconel 52 diameter 0.035in. (0.9 mm).
- One pass per layer.
  - String bead.
  - Pass thickness: 0.08in. (2mm).
  - Deposition rate: 650 gm/hr.
- Chanfer width 0.315 in. to 0.475 in. (8 to 12 mm).

DMW Thermal Conditions and PWHT

> **Thermal conditions.**
  - **Preheating**
    - **347°F/437°F (175°C/ 225°C) (side low alloy steel)**
  - **Interpass temperature**
    - **maximum 437°F (225°C)**
  - **Postheating**
    - **392°F/464°F (200 °C/240°C) during 3h**

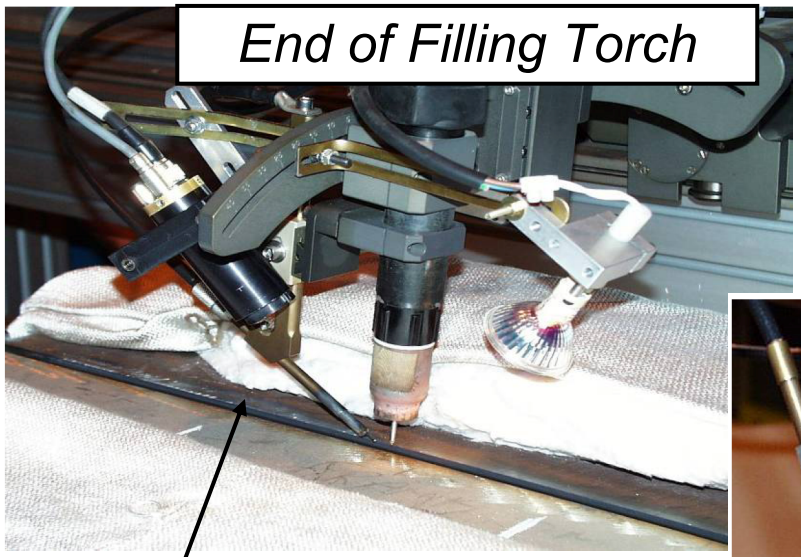
> **Stress relieve heat treatment**
    - **1130°F (610°C) 16h (process qualification maximum time)**



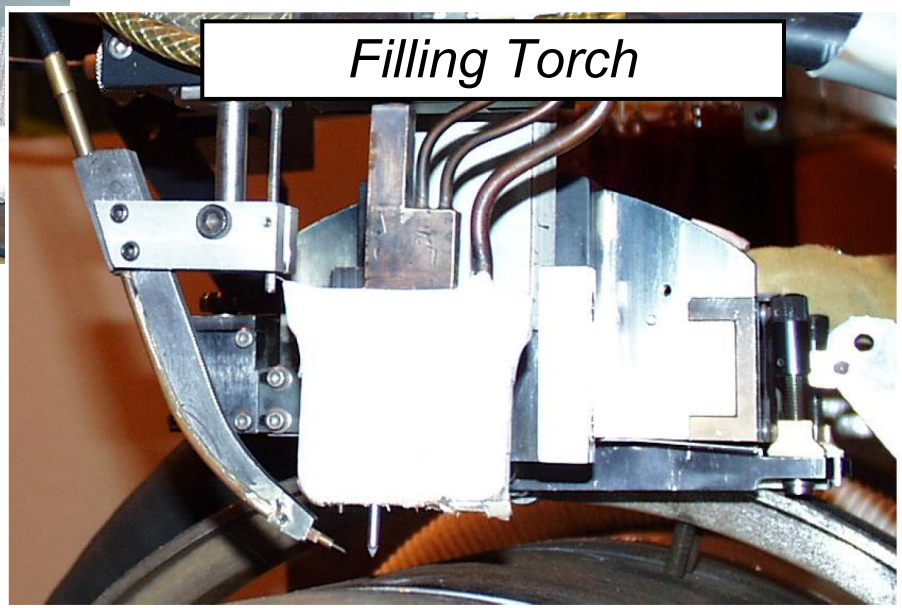
Gas furnace for Stress Relieve Heat Treatment

DMW Welding Equipment

GTAW Torch

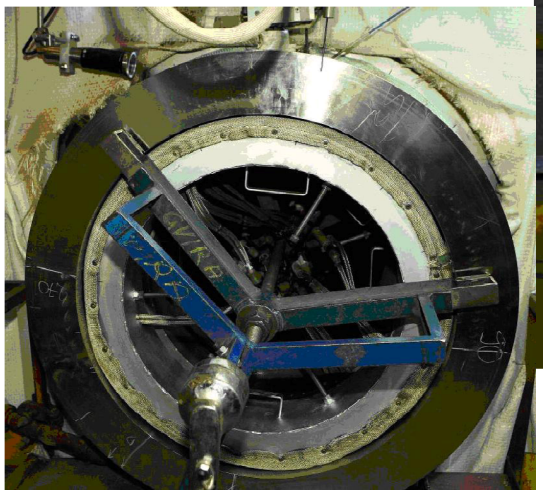


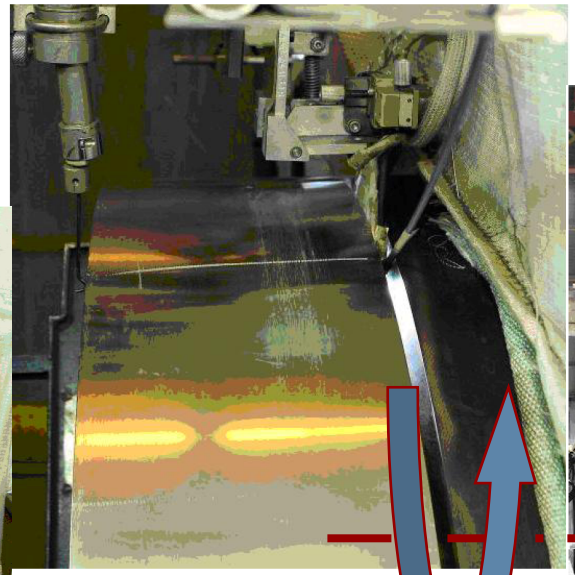
Camera system

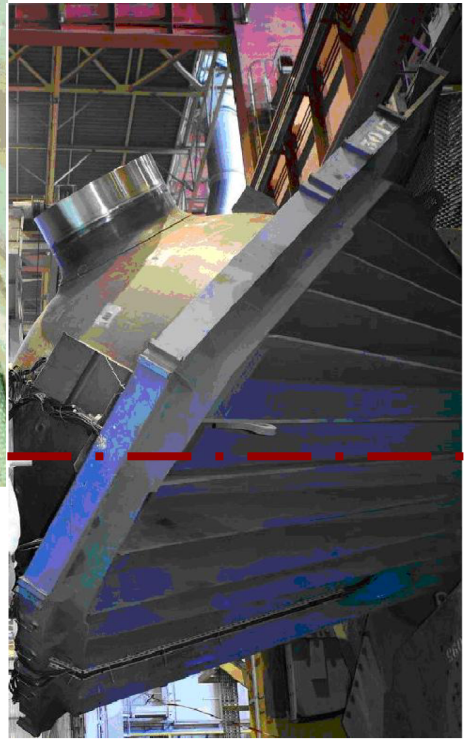


DMW Manufacturing

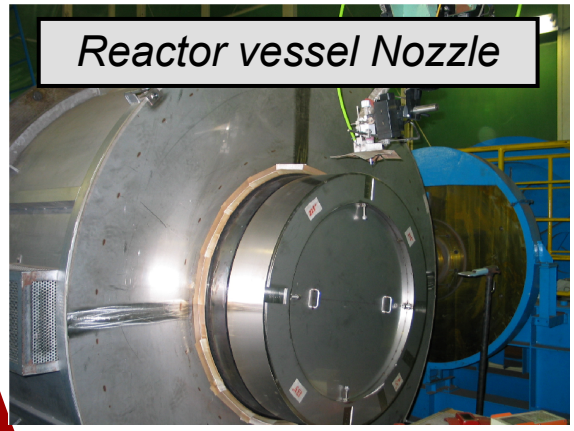
Steam generator



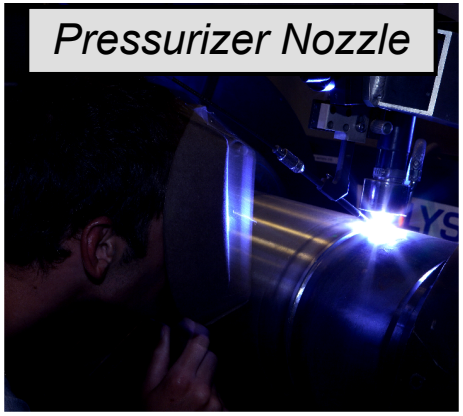




Reactor vessel Nozzle



Pressurizer Nozzle

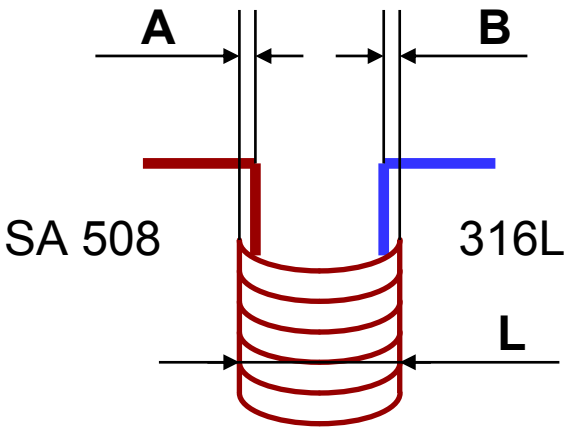


DMW Dilution Control

> **Geometrical side wall dilution.**

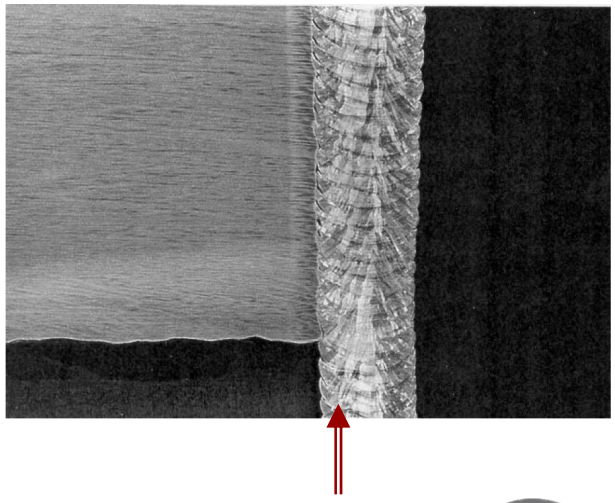
(A + B) / L = 10 to 15 %.

- **Low side wall dilution and good reproducibility provide good metallurgical quality in the weld deposit.**



> **Chemical composition of the weld deposit in contact with primary water:**

- **Percent Cr Content > 26%**
- **No risk of stress corrosion cracking (SCC).**

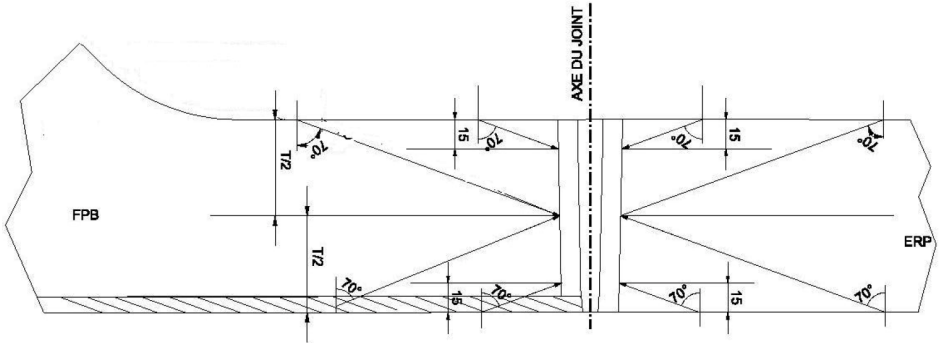


DMW Non Destructive Examination

> **Surface examination.**
  - **Visual examination and Liquid penetrant examination (ID and OD).**

> **Radiographic examination.**
  - **Gamma rays: Cobalt 60.**
  - **Following are unacceptable:**
    - **Porosities > 0.16 in. (4mm).**
    - **Lack of fusion.**
    - **Cracks.**
    - **Inclusions L > 0.78 in. (20mm).**

> **Ultrasonic examination**
  - **Longitudinal Waves: 0°, 70°.**
  - **Based on side drilled hole Ø 0.078 in. (2mm) for 70° probe and FBH Ø 0.236 in. (6mm) for 0°probe**
  - **Acceptance criteria:**
    - **No lack of fusion: along side walls and between passes.**



Defect Types and Possible Weld Repair

- What possible kind of defect ?
  - Defect types found with the GTAW process in NG.
    - Porosity (weld process with gas) and tungsten inclusion .
    - Lack of fusion side wall: no risk, tolerant welding process.
    - Interpass lack of fusion: no risk flat position welding and good interpenetration passes).
  - Welding with Alloy 52.
    - Hot cracking: bead shape very good to avoid it.
    - Micro cracking/ductility dip cracking: low dilution with materials (SS and low alloy steel) and free axial shrinkage are favorable to achieve a good quality weld deposit.
    - Root passes are machined off.
- Strategy for repair.
  - Surface defects: manual process.
  - Internal defects: total weld elimination and rewelding with the same welding procedure.

The welding process is robust, simple, and does not require any repair

DMW Industrial Applications

- Finland EPR (OL3).
  - DMW steam generators and pressurizer.
    - Manufactured in France: AREVA Saint Marcel plant 2007 & 2008.
  - DMW reactor vessel.
    - Manufactured in Japan for AREVA: (MHI company) 2006.
- France EPR (FA3) - Manufactured in France: AREVA Saint Marcel plant.
  - DMW reactor vessel 2008-2009.
  - Steam generators and pressurizer.
    - Ongoing manufacturing .
- China EPR (Taishan 1 & 2).
  - DMW manufacturing not yet started.
  - One plant will be manufactured in France, the other in China.

For the first EPR, DMW manufacturing was a success

Metallurgical and Mechanical Characterization

Chemical Compositions

Weld Metal

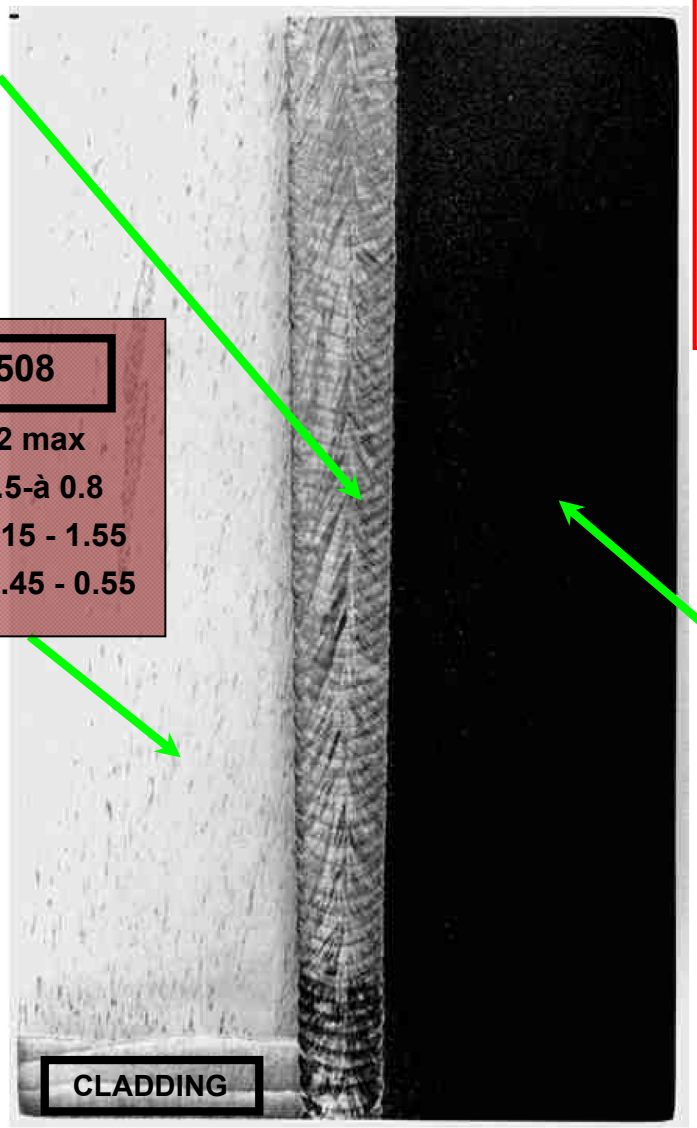
%Ni = 52.6
%Cr = 26.21
%Fe = 19.1

INCONEL 52 WIRE

% C = < 0.040
%Cr = 28 - 31.5
%Fe = 8 - 12
%Ti = < 1 %Al = <1.1
%Ni = bal.

A 508

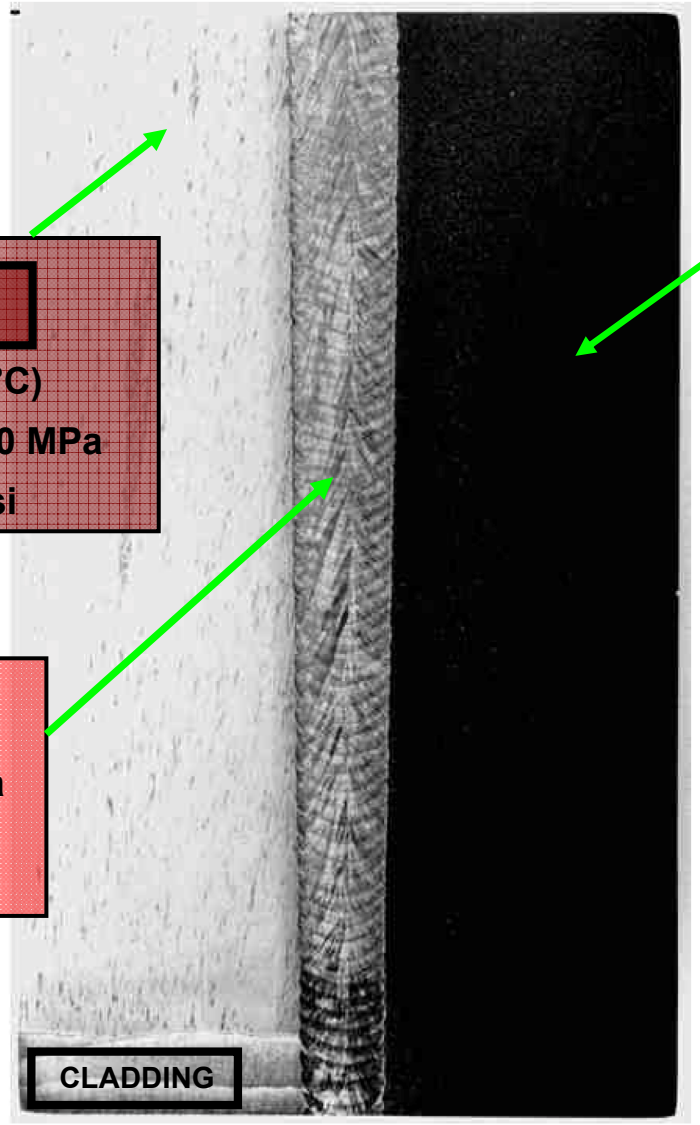
% C = 0.2 max
%Ni = 0.5-à 0.8
%Mn =1.15 - 1.55
%Mo = 0.45 - 0.55



316 L + N

% C = < 0.035
%Ni = 11.5 - 12.5
%Cr = 17 - 18.2
%Mo = 2.25 - 2.75

Tensile Properties



A 508

68°F (20°C)

UTS 550 / 670 MPa

80/97 ksi

316L + N

68°F (20°C)

UTS > 520 MPa

75 ksi

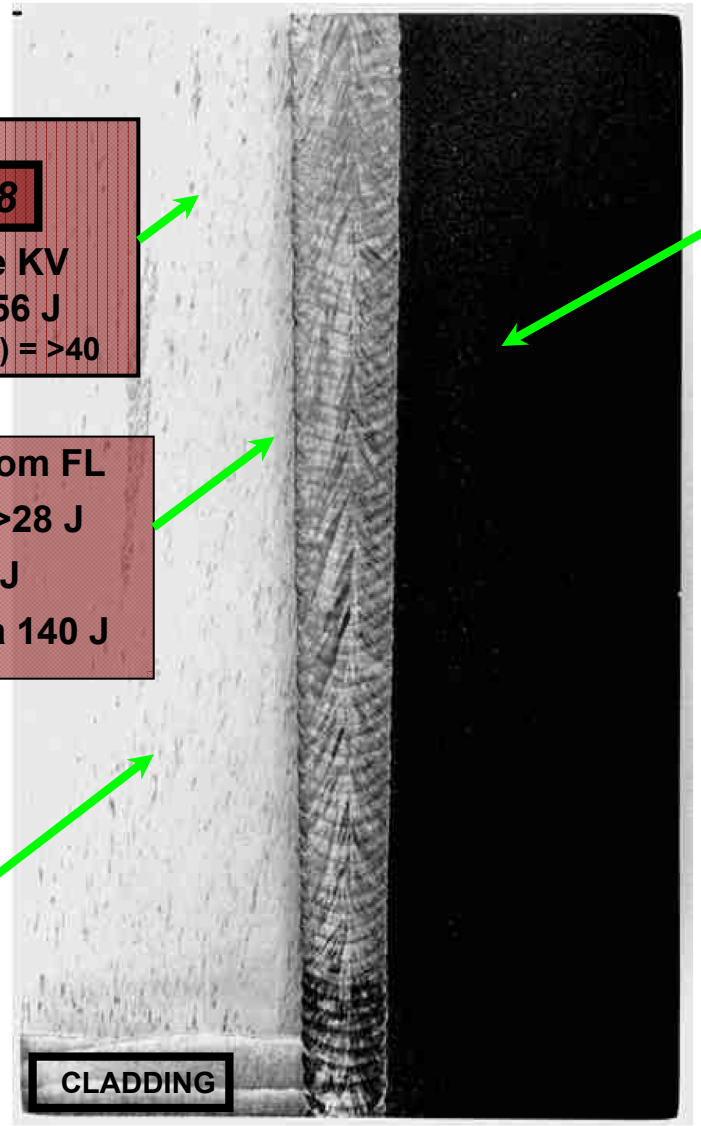
Weld Metal

UTS(RT) 550 – 750MPa

80-109 ksi

Typical 680 MPa/99ksi

Charpy Toughness Properties



A 508
Average KV
0°F = >56 J
- 4°F (-20°C) = >40

316 L + N
Average KV
68°F (20°C) = >60 J

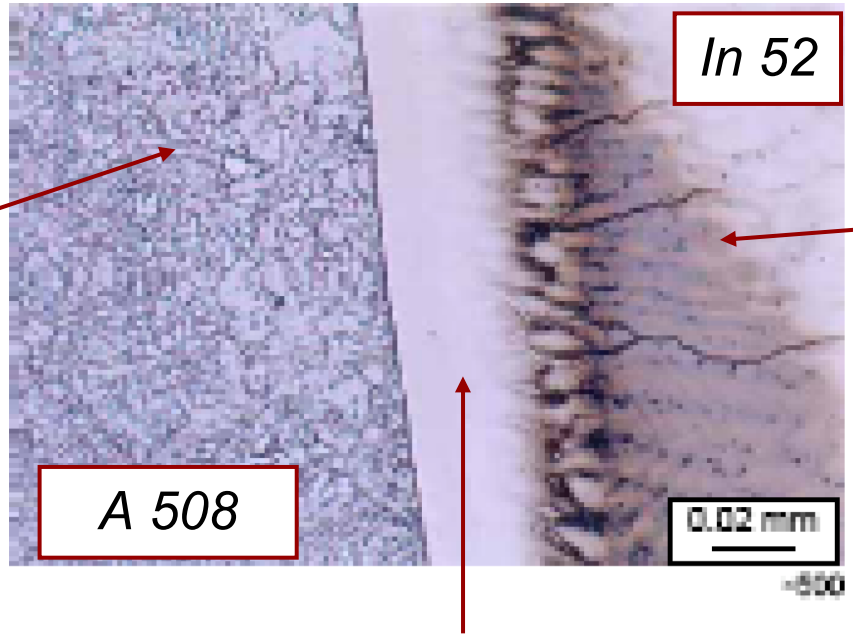
HAZ A 508 1 mm from FL
KV - 4°F (- 20°C) = >28 J
Average = > 40 J
Typical Average 75 à 140 J

Weld Metal
68°F (20°C) = >60 J
Typical 185 - 195 J

Microstructure at the Fusion Line

> **Microstructure at the fusion line was studied by optical and transmission electron microscopy.**

Decarburized Heat Affected Zone (HAZ)



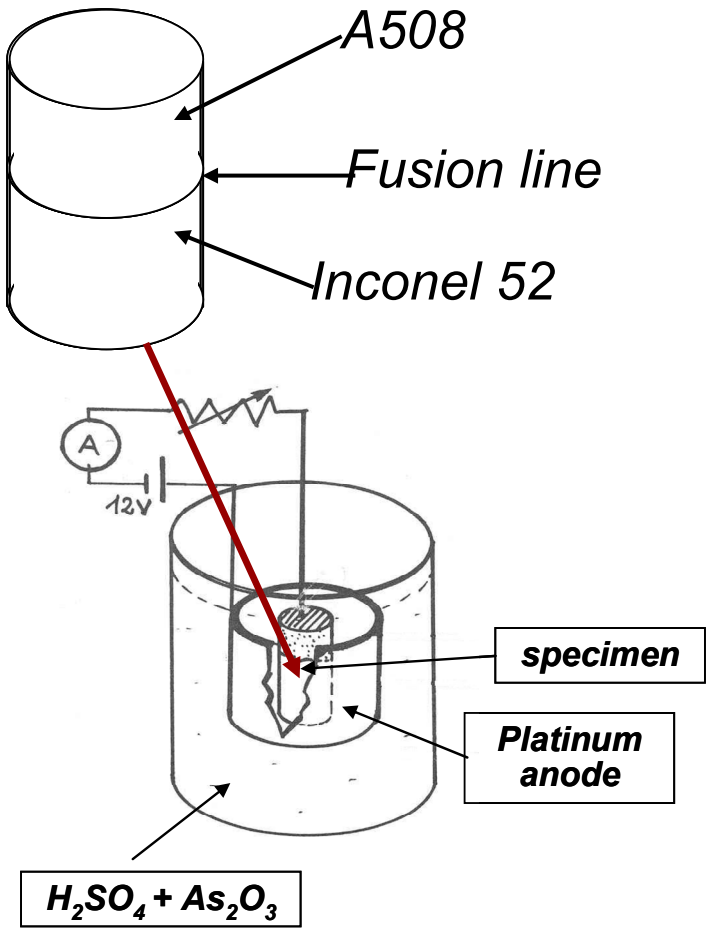
Ni base solidification structure + carbide precipitation

White Layer: Austenitic zone + dense carbide precipitation

Unlike SS DMW, there is no martensitic layer at the fusion line (no risk of hydrogen embrittlement/disbonding)

In-Service Hydrogen Embrittlement

> **Test of resistance to hydrogen cracking: cathodic charging of a specimen, after PWHT.**



> **Characterizes HAZ or DMWs susceptibility to hydrogen.**

> **Hydrogen cathodic charging in boiling H2SO4:**
  - **Current density = 50 or 10 milliamps/cm2.**
  - **Holding time = 48 hours.**

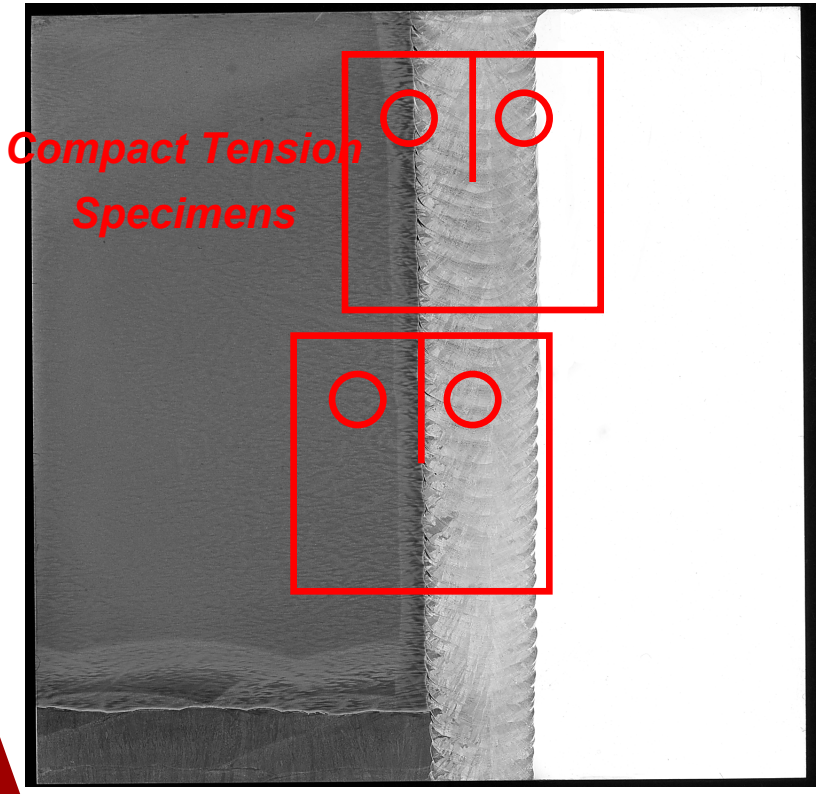
> **Cracks observed only in HAZ and base metal (BM) (severe test) - no crack near the fusion line.**

> **The fusion line of narrow gap DMW is insensitive to H2 embrittlement.**

Corrosion Tests – Resistance to Primary Water SCC (PWSCC)

Fracture Toughness – Ductile Tearing Resistance at 572°F (300°C)

> **Ductile tearing resistance tests at 572°F (300°C) (ASTM E1820) of narrow gap DMW with Inconel 52.**

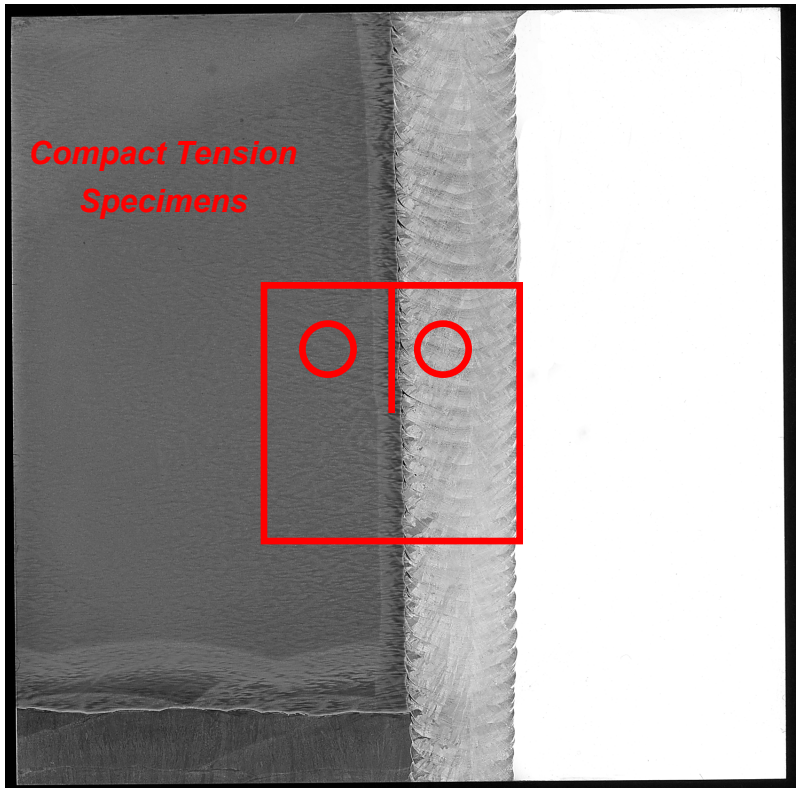


> **Location of the specimen:**
- **Fatigue precrack in the center line.**
- **Fatigue precrack on the fusion line.**

Fracture Toughness – Ductile Tearing Resistance at 572°F (300°C)

Fracture Toughness – Low Temperature Tests in the Brittle/Ductile Transition

> **Study of brittle/ductile transition in the decarburized HAZ.**



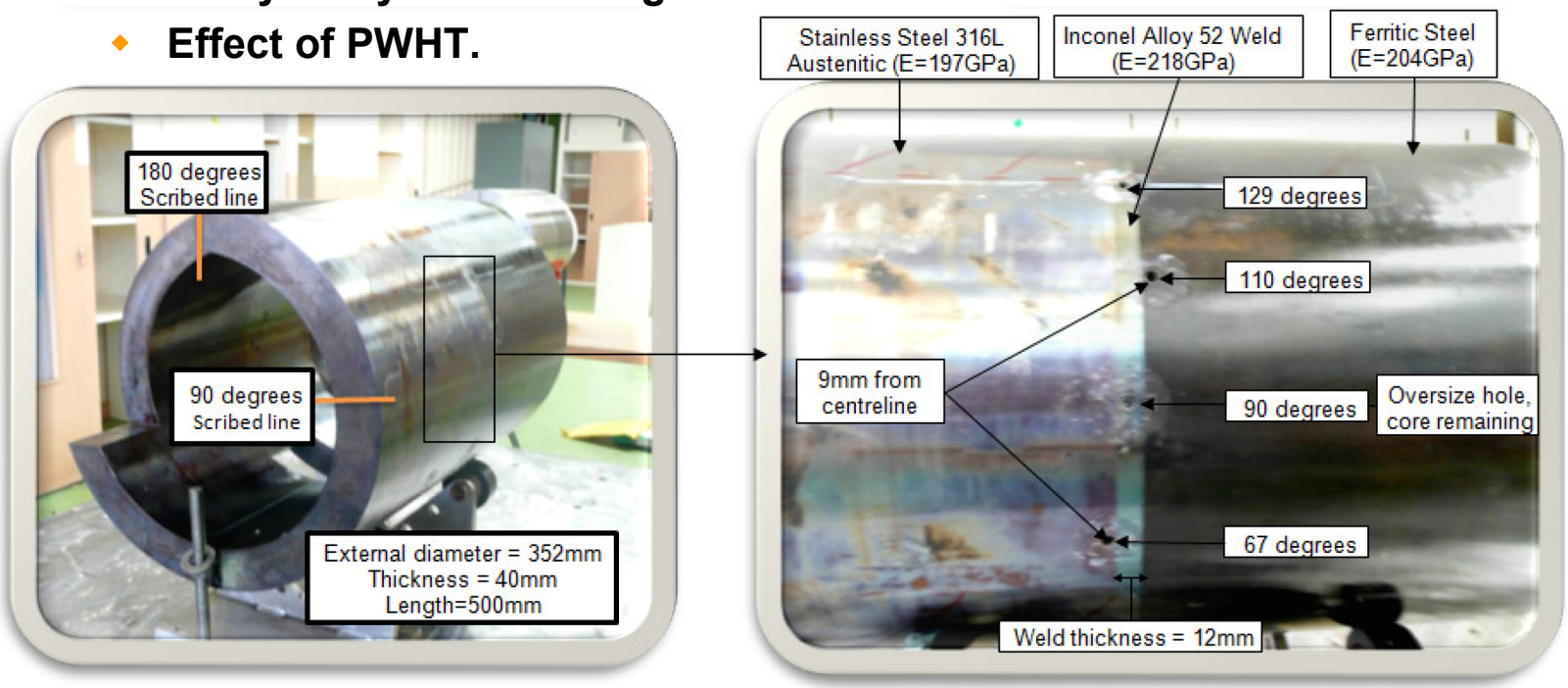
> **Tests conducted :**

- **Fatigue pre-crack tip located:**
  - **Close to the fusion line.**
  - **On the side of A508 decarburized HAZ.**
- **As per ASTM E1921 standard (measurement of KJc).**
- **In a temperature range from -148°F (-100°C) to -22°F (-30°C).**
- **On 1TCT (one inch thick compact tension) specimens.**

Fracture Toughness – Low Temperature Tests in the Brittle/Ductile Transition

Residual Stress Measurements

> **Program of residual stress measurement conducted.**
- **Two different narrow nap DMW sizes.**
- **Different measurement techniques (neutron diffraction, deep hole drilling (DHD)).**
- **Analysis by FEM welding simulation.**
- **Effect of PWHT.**



Residual Stress Measurements

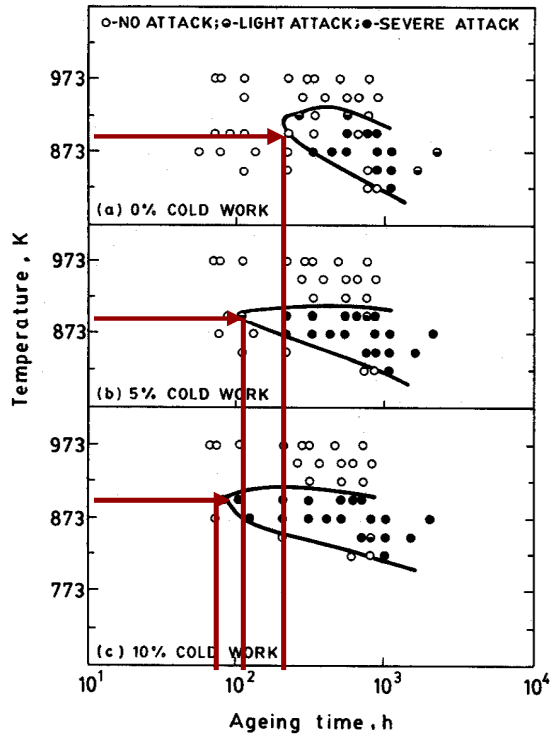
Effect of PWHT on Safe Ends

Effect of PWHT on Safe Ends

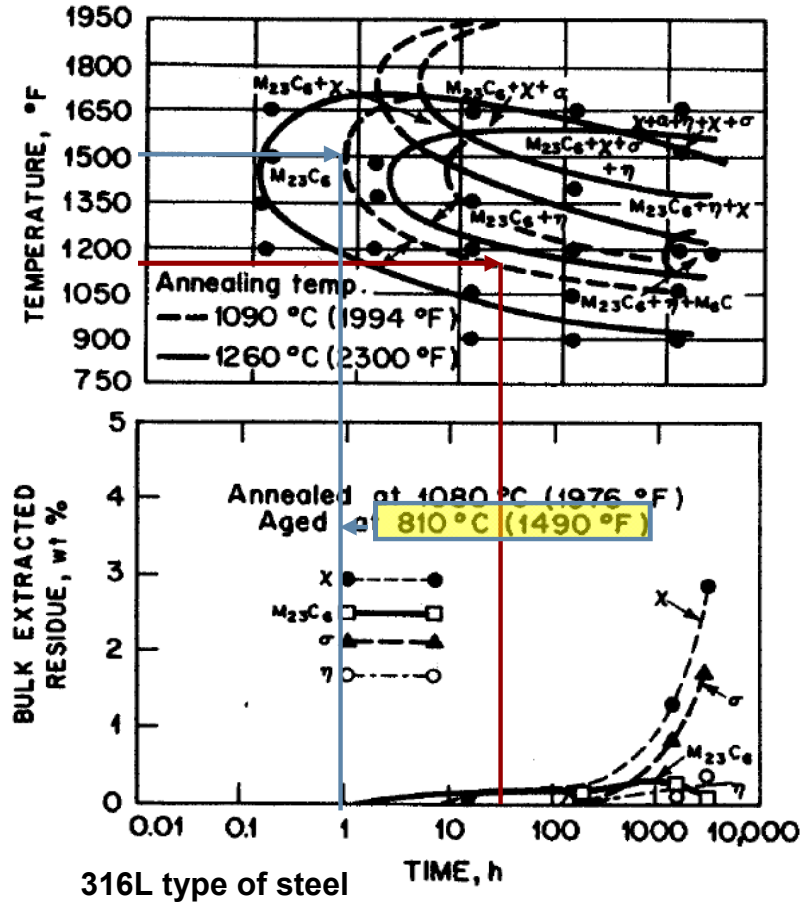
- PWHT is performed at T ≤ 1150 °F (620°C) for a cumulated duration ≤ 16h.
- Material of the safe end is an austenitic SS with low carbon (type 316L – or 316L with controled nitrogen (N ≤ 0.080%)).
- With this type of steel and the conditions of heat treatment, the following are avoided:
  - Precipitation.
  - Intergranular sensitization.
- PWHT has no effect on safe ends.
  - Corrosion resistance.
  - Mechanical properties.

Intergranular Sensitization and Carbide Precipitation in Low Carbon SS Type 316

N. Parvathavarthini, R.K. Dayal and J.B. Gnanamoorthy "Influence of prior deformation on the sensitization of AISI Type 316LN stainless steel" Journal of Nuclear Materials 208 (1994) pp 251-258



Handbook of stainless steels – D. PECKNER, I.M. BERNSTEIN , McGraw Hill Book Company 1977.



316LN type of steel

- **C = 0.03%**
- **Ni = 12.2%**
- **Cr = 16.6 % - Mo=2.61 %**
- **N=0.086 %**

Intergranular sensitization tests in boiling Cu-CuSO4-H2SO4

316L type of steel

- **C = 0.02%**
- **Ni = 14.2%**
- **Cr = 16.4 % - Mo=2.99 %**

Time-temperature precipitation diagram

Conclusions

Conclusions

- DMW without butter weld.
  - Simplification of the process (no butter welding nor inspection).
- High quality of welding.
  - Automatic GTAW (high reproducibility).
  - Sound and compact weld.
- Narrow gap geometry.
  - Smaller amount of deposited metal.
  - Thickness of the weld from 0.8 in. to 5.1 in. (20mm to 130 mm).
- Weld pocess easy to operate.
  - Welding in flat position only
  - One unique bead position.
- NDT examination.
  - Weld geometry makes NDE easier.
    - 1 g Ray radiograph for both sides of weld.
    - Better geometry for UT.

Conclusions (cont'd)

- Excellent properties of the weld.
  - Good control of the dilution/chemical composition of weld metal.
  - Good mechanical properties of Inconel 52.
- Good resistance to PWSCC initiation of weld metal and interfaces.
- Microstructure at the fusion line.
  - Microstructure free of martensite.
  - Fusion line is not sensitive to hydrogen embrittlement.
  - Fusion line is tough.
    - High tearing resistance.
    - Ferritic HAZ has a low equivalent RTNDT.
- Residual stresses are moderate.
  - Limited amount of deposited weld metal and PWHT.

Basis for selecting the narrow gap GTAW DMW with Inconel 52 filler metal for U.S. EPR