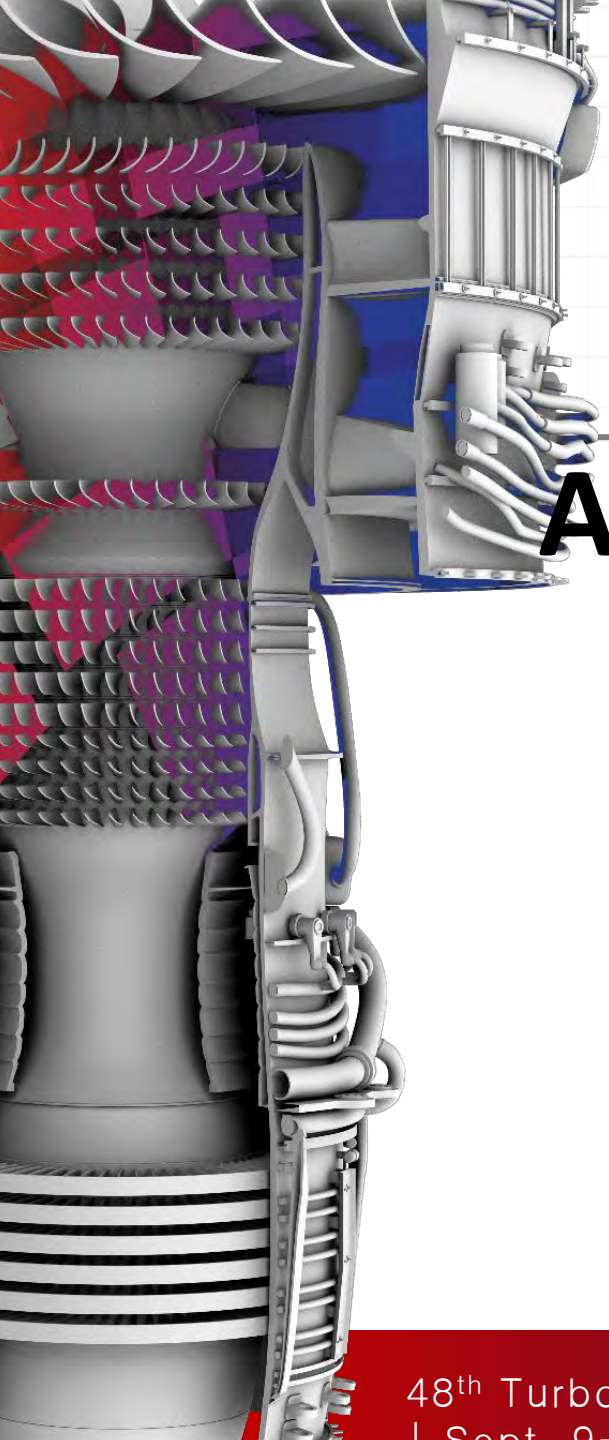


TURBOMACHINERY & PUMP SYMPOSIA

Analysis and countermeasure for Sulfide Stress Cracking of Centrifugal compressor

Sanggyn Kwon / Bumsu Kim

Sangjoo Lee / Seokho Seo

Presenter/Author bios

Presenter, Mr. Sanggyn Kwon

Engineer in Rotating machinery Reliability & Engineering Team of SK Energy, Korea, since 2012.

Received a B.S.degree (Material Engineering from Yonsei University, Korea).

Co-author. Mr. Bumsu Kim.

Team Leader of Rotating machinery Reliability & Engineering Team for SK Energy, Korea.

Received a B.S.degree (Mechanical Engineering from Busan National University, Korea)

and a key member of KRMEA(Korea Rotating Machinery Engineers Association).

Co-author. Mr. Sangjoo Lee .

Rotating machinery engineer in reliability for SK Energy, Korea, since 2007.

Received a M.S. degree(Mechanical Engineering from Ulsan University, Korea) and a key member of KRMEA(Korea Rotating Machinery Engineers Association)

Co-author. Mr. Seokho Seo .

Rotating machinery engineer in reliability for SK Energy Ulsan, Korea, since 2007.

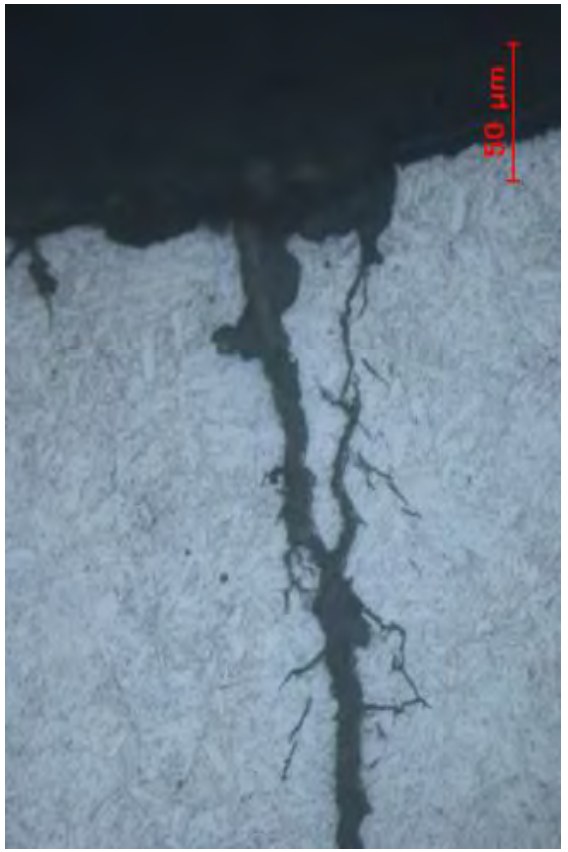
Received a B.S. degree(Mechanical Engineering from Kyungbuk University, Korea)

In this case study

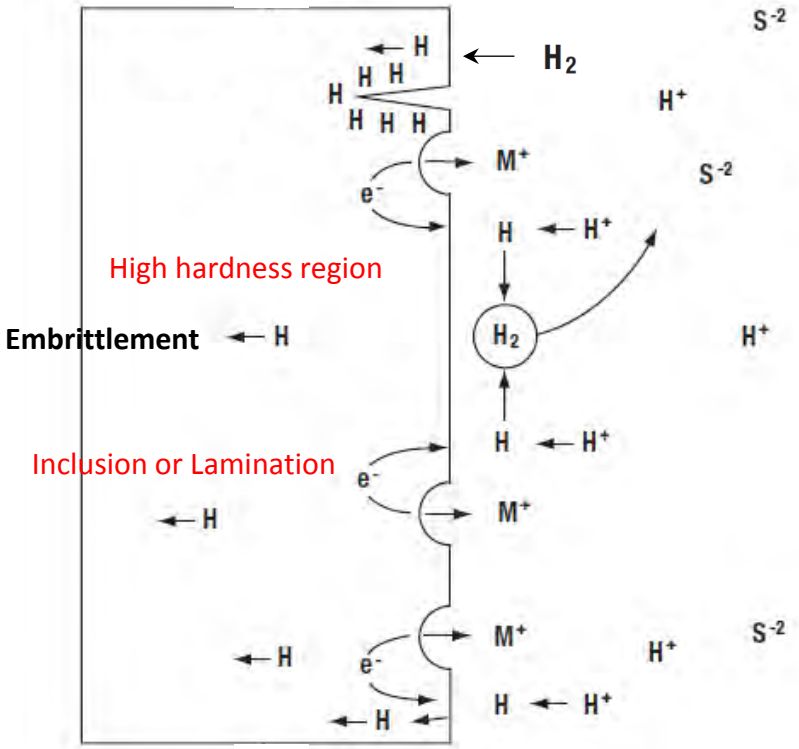
In case of compressors operated in environment of wet hydrogen sulfide, **Sulfide Stress Cracking** could act critical mechanism of impeller failure. This C/S deal with what make sulfide stress cracking and how to take a countermeasure to prevent recurrence of sulfide stress cracking, based on 2 cases of impeller failure from recycle gas compressor of Middle Distillation Unit(MDU) and Residue Hydro De-sulfurization Unit (RHDS) in refinery plants.

1. What is Sulfide Stress Cracking?

- Sulfide stress cracking (SSC) is a form of **hydrogen embrittlement** which is a cathodic cracking mechanism. Susceptible alloys, especially steels, react with hydrogen sulfide, forming metal sulfides and atomic hydrogen as corrosion byproducts. **Atomic hydrogen** either combines to form H2 at the metal surface or **diffuses into the metal matrix.**
- Sulfide stress cracking has special importance in the gas and oil industry, as the materials being processed there (natural gas and crude oil) often contain considerable amounts of hydrogen sulfide.



2. Step of Sulfide Stress Cracking



Step1. Sulfide corrosion on metal surface

- Generation of hydrogen atom

$$Fe + H_2S \leftrightarrow FeS + 2H^0$$

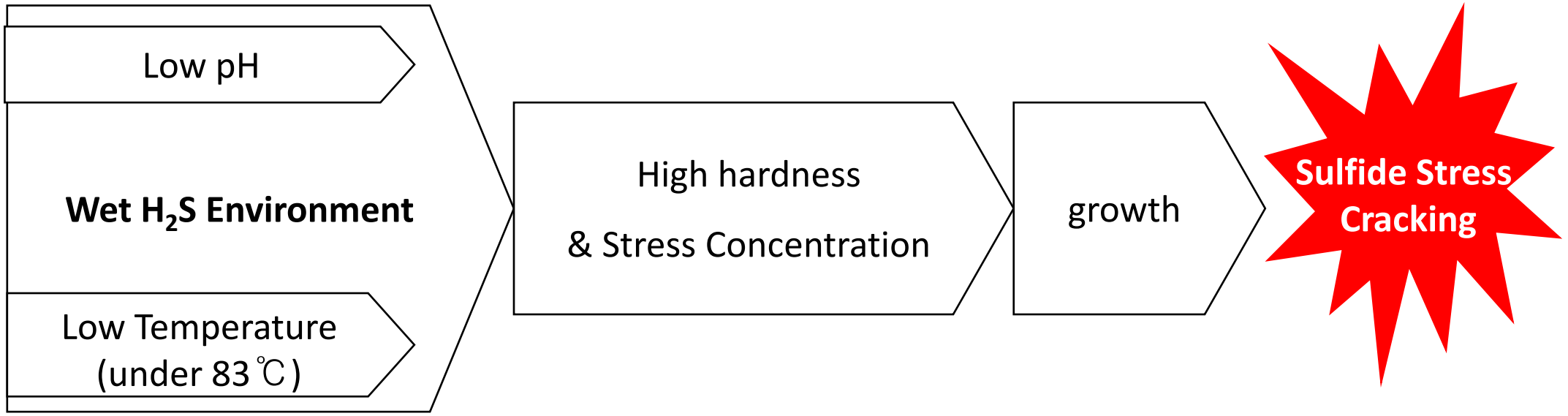
Step2. Hydrogen diffusion

Step3. Hydrogen Collecting

- Collected on High Hardness region
- Hydrogen embrittlement

Step 4. Growth of Crack with intergranular mode

3. Mechanism of Sulfide Stress Cracking



Metal corrosion and
Generation of Hydrogen atom
(H_2S + Fe →FeS + 2H)

Hydrogen Atom collecting
on high hardness position

Hydrogen Embrittlement

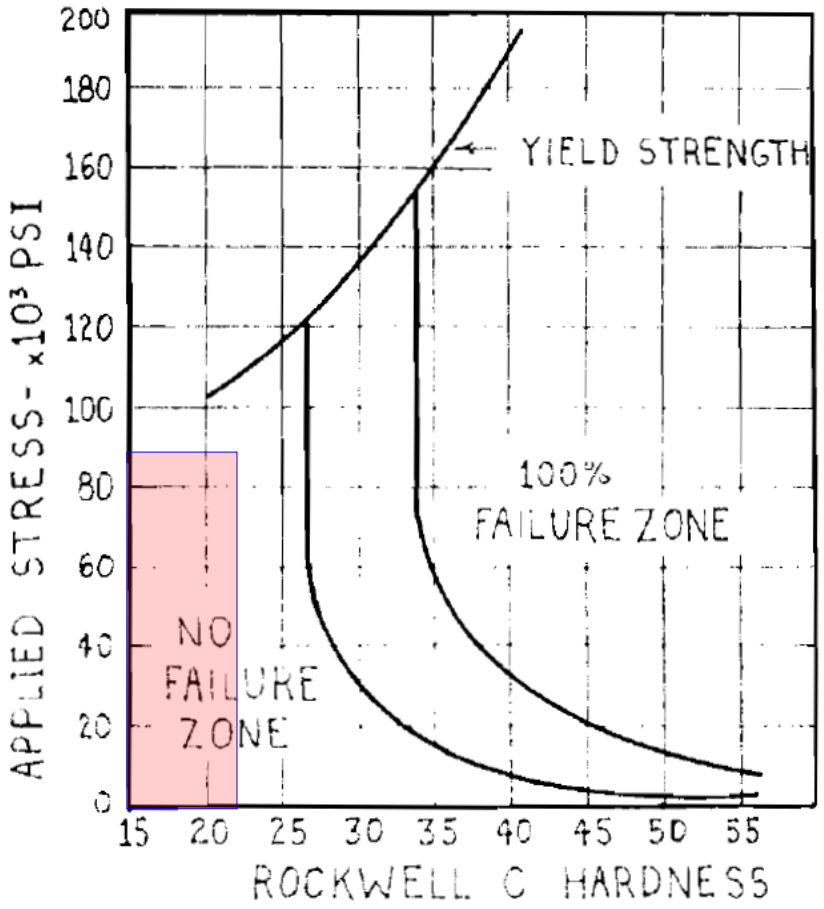
Intergranular
mode

4. API Recommendation : API 617 8th edition

- **4.5.1.6** Unless otherwise specified, if hydrogen sulfide has been identified in the gas composition, materials exposed to that gas shall be selected in accordance with the requirements of NACE MR 0103-2007 and where applicable, the referenced NACE SP 0472-2008.

- **4.5.1.8** Ferrous materials not covered by NACE MR 0103-2007 or NACE MR 0175-2008 shall have amaximum yield strength of 620 N/mm2 (90,000 psi) and a maximum Rockwell hardness of HRC 22.Components fabricated by welding shall be postweld heat treated, if required, so that both the weld and the heat-affected zones meet the yield strength and hardness requirements.

※ Experiment result for AISI4140 material



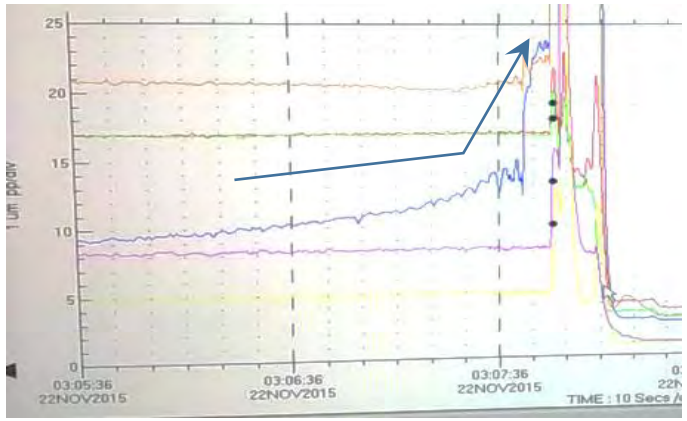
Case Study

Trouble Shooting Case 1

Trouble History and Information

1. Trouble History

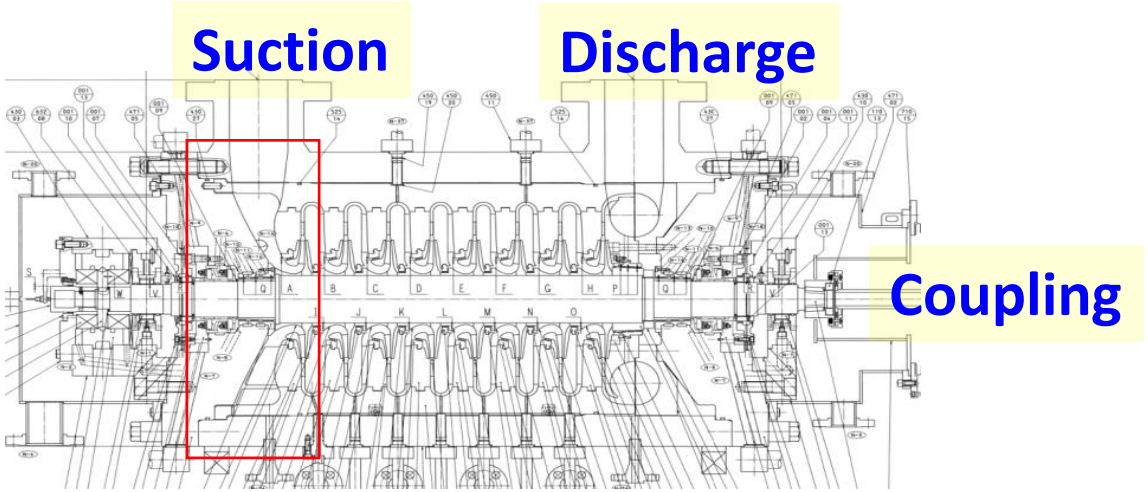
- Trouble year and equipment : 2015. Centrifugal compressor
- Source : Compressor Trip by Vibration High-High on Low Pressure Casing
- Position : 1st Impeller
- Vibration Trend : Rapid increasing to 320㎛ just before the trip



2. Equipment Information

Process	Middle Distillation Hydro-desulfurization Unit
Initial Start-up	1991
Equipment Function	Recycle Gas Compressor
Service Gas	Main Hydrogen with other contents
Suction / Discharge Pressure (kg/cm2g)	37.77 / 56.25
Driver	Steam Turbine

Inspection



- 1st impeller was cracked completely
- Wet contaminant on suction side
- Heavy fouling on labyrinth

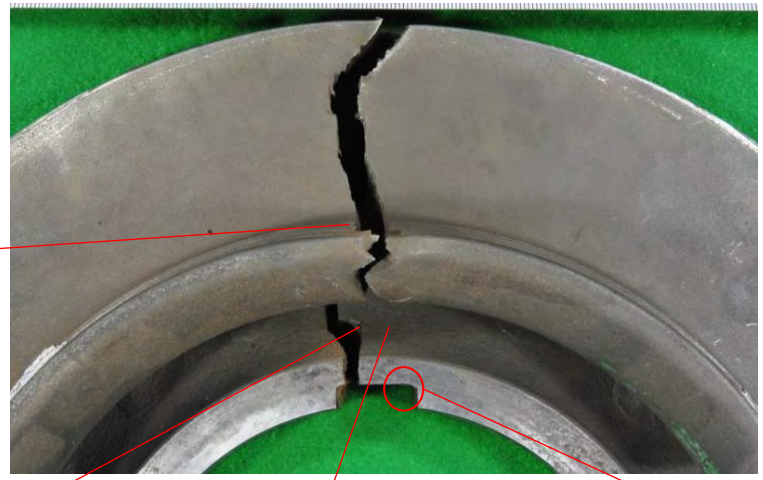
1st Impeller

Suction Side

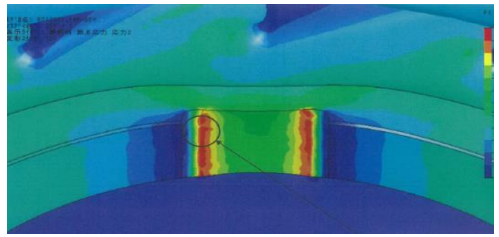
Labyrinth

Fractography

1 Crack initiated from Key groove of impeller

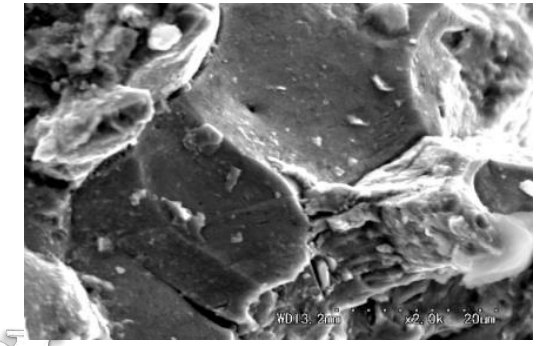


2 Stress concentrated on Key groove

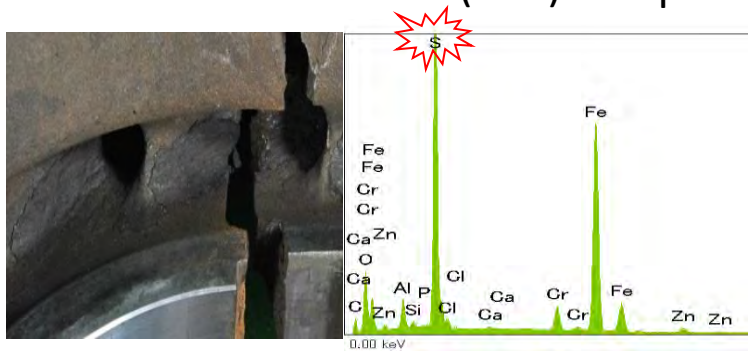


3 **Hardness of Impeller : Max HB 261**

4 Intergranular Crack



5 High concentration of Sulfur on Surface (EDS) and pH4



6 Additional Cracks on Key Groove (w/Corrosion pit , 2nd Crack)

Corrosion Pit

Root Cause Analysis

Features	Material & Design	Environment
• Inter Granular Crack • Secondary Crack • Crack initiated from Key Groove	• High Hardness[1)] (HB 261) • Stress Concentration on Key Groove	• Wet H2S Gas Composition • Low pH (pH4) • Low Temperature (49℃)

Sulfide Stress Cracking

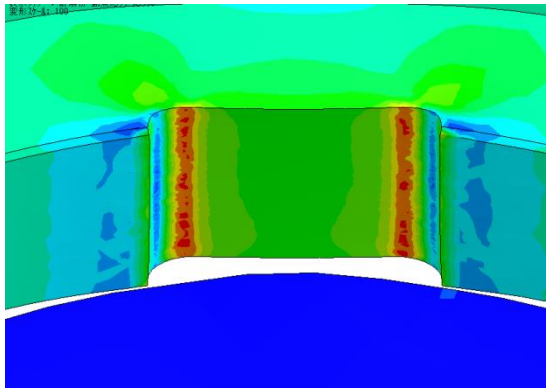
Countermeasure

1. To approve the corrosion resistance

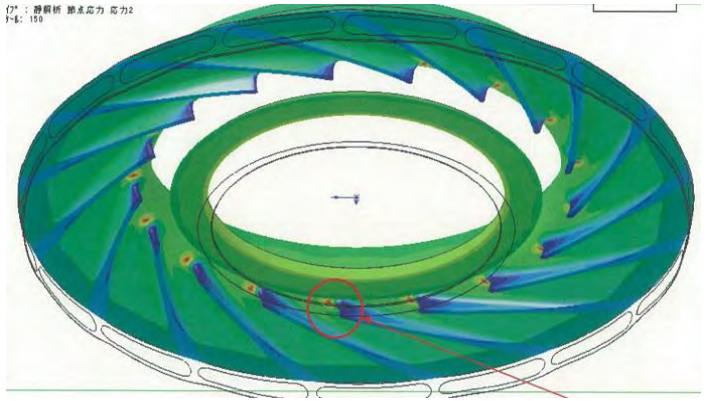
- High alloy steel selection to improve for corrosion resistance
- Material selection according to NACE MR0103 for Wet H2S environment (Hardness)

2. To decrease the stress concentration

- Avoiding high stress concentration on rotor (Keyless type impeller)



Key Assembly



Keyless Assembly

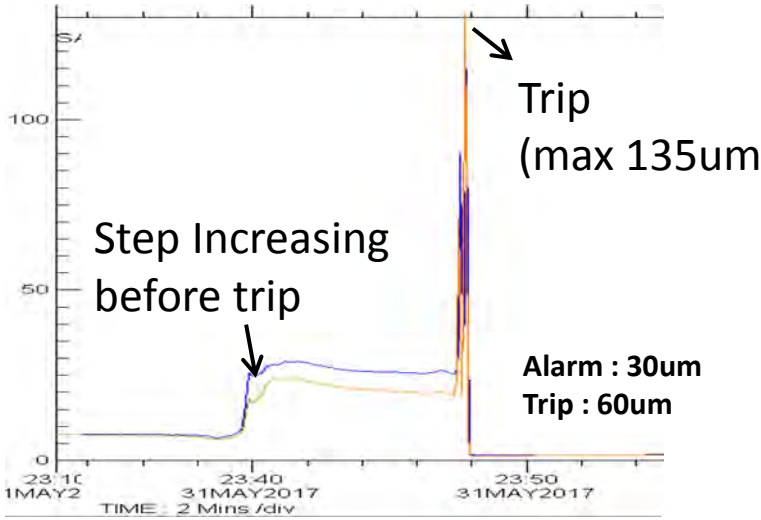
Case Study

Trouble Shooting Case 2

Trouble History and Information

1. Trouble History

Trouble year : 2017.
Source : Compressor Trip by Vibration High-High on Low Pressure Casing
Position : 1st Impeller
Vibration Trend : step changed and tripped in a few minutes



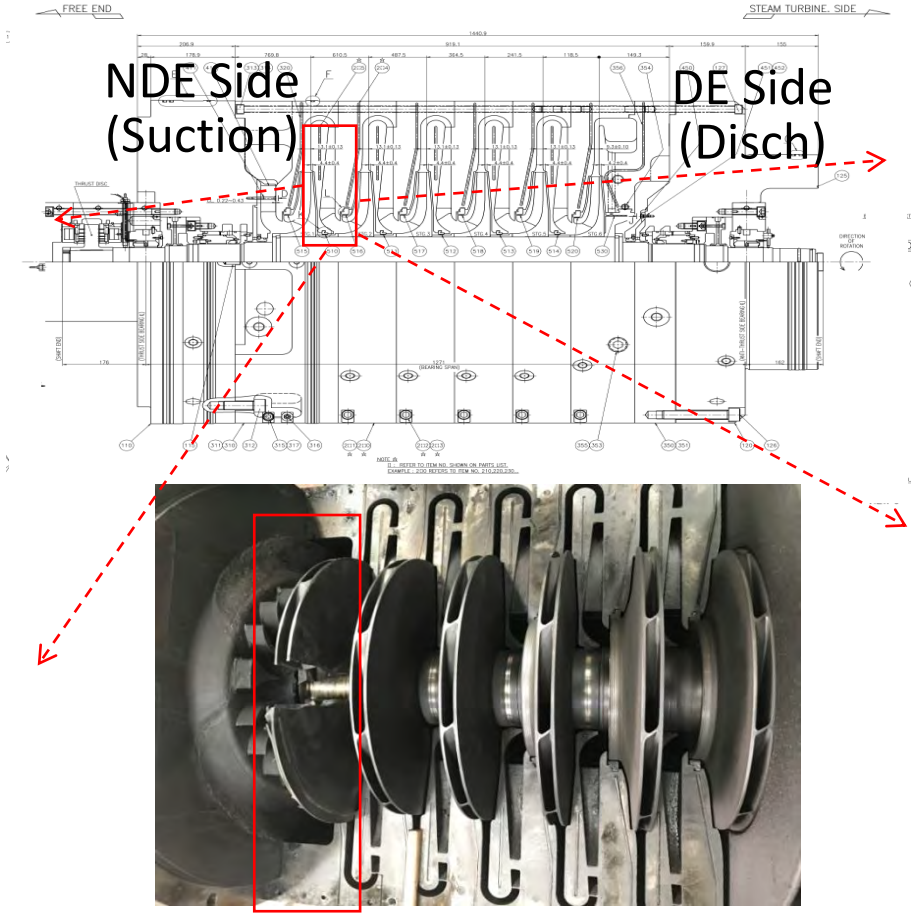
2. Equipment Information

Process	Residue Hydrogen De-Sulfurization
Initial Start-up	1997
Equipment Function	Recycle Gas Compressor
Service Gas	Main Hydrogen with other contents
Suction / Discharge Pressure (kg/cm2g)	164 / 209
Driver	Steam Turbine

Inspection

1 1st Impeller

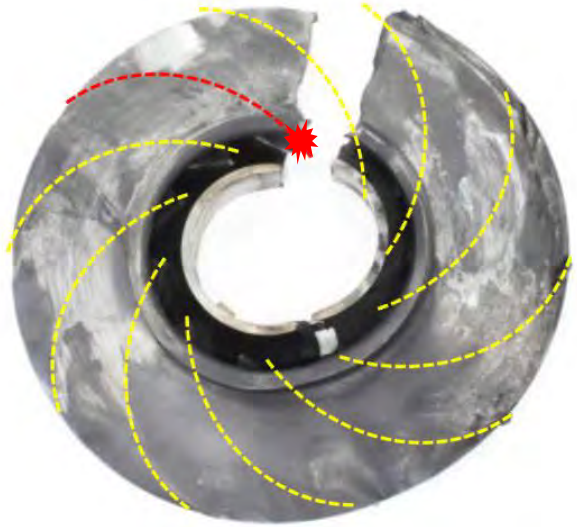
2 1st Impeller Shaft

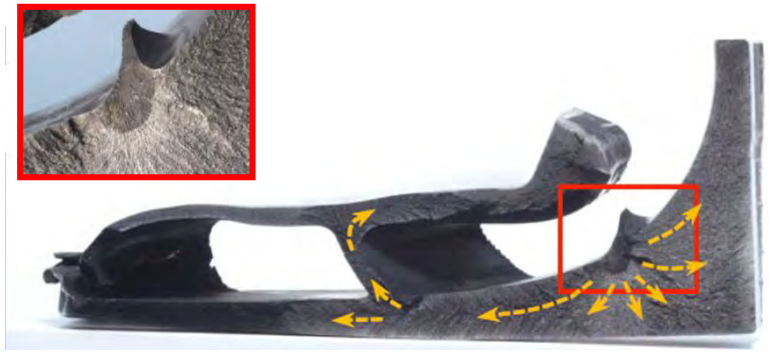


3 1st Labyrinth

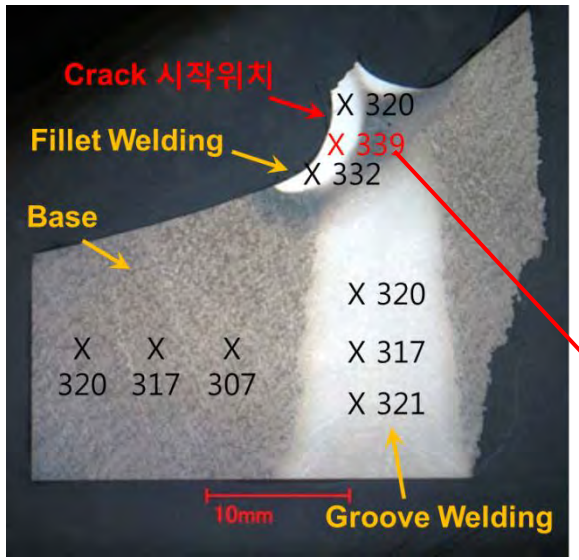
4 Diaphragm

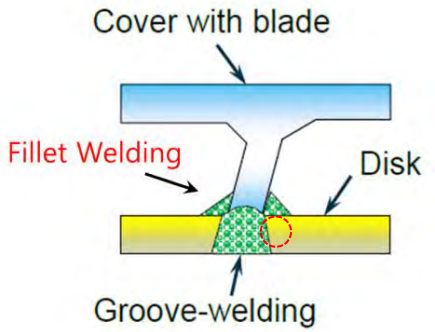
Fractography



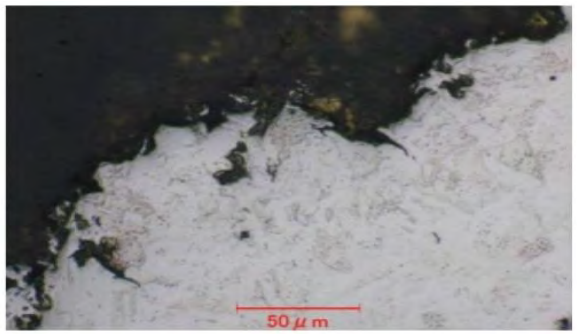


Crack propagation with Chevron Pattern

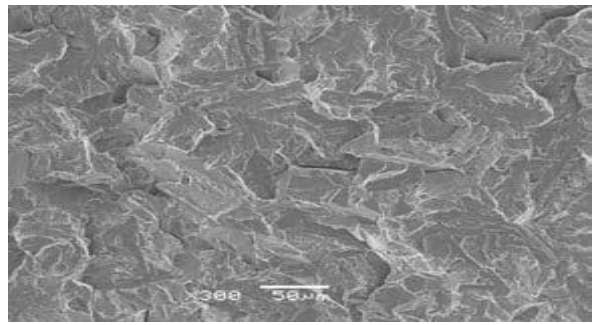




Hardness of Initiation Point
Max HB 339 (NACE Limit HB311)



Corrosion & Residual cracks at initiation Point



Quasi-Cleavage Pattern on crack surface

Root Cause Analysis

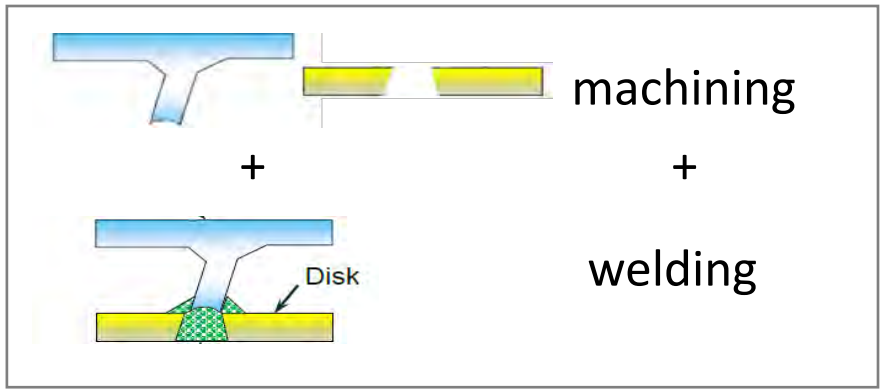
Features	Material & Design	Environment
• Embrittlement crack - Chevron Pattern - Residual cracks - Quasi-Cleavage Pattern	• High Hardness (HB 339) • Welding area which High stress is concentrated	• Corrosion environment due to Wet H2S Gas Composition • Low Temperature (59℃)

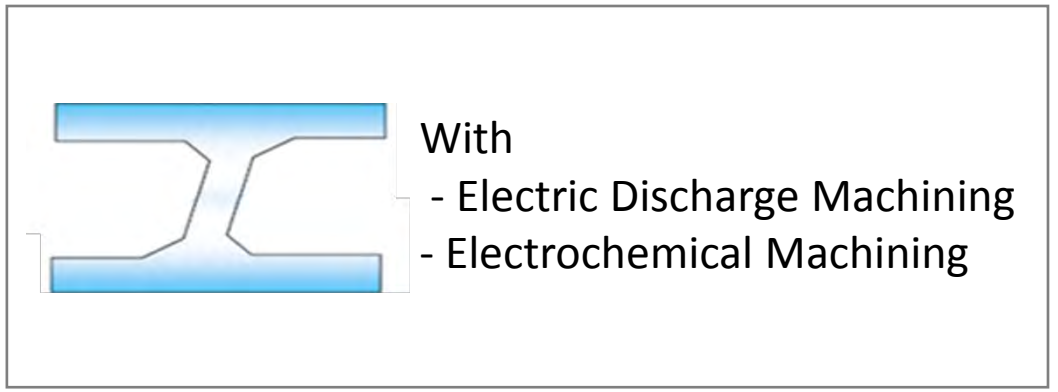
Sulfide Stress Cracking

Countermeasure

1. To prevent incorrect post weld heat treatment process

- WELDLESS impeller



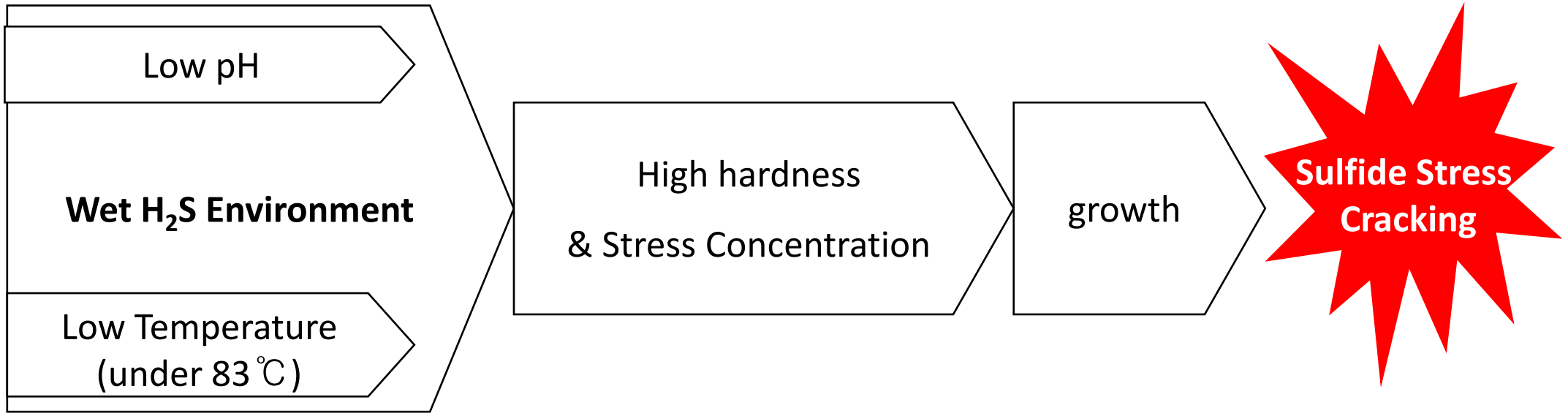


2. To inspect sulfide stress cracking

- Periodical hardness measurement with portable devices (Vickers hardness)
- Periodical inspection by WFMT(**W**et **F**luorescent **M**agnetic particle **T**est)
  (cracks underneath the surface, which cannot defines by PT inspection, can be inspected by WFMT)

Summary

SSC mechanism



Metal corrosion and
Generation of Hydrogen atom
(H_2S + Fe →FeS + 2H)

Hydrogen Atom collecting
on high hardness position

Hydrogen Embrittlement

Intergranular
mode

Recommendations

<u>If the process contains H2S and H2O (Wet H2S) even small amount,</u>

Design	Material Selection	• **High alloy steel** selection to improve the corrosion resistance • **Material selection according to NACE MR0103** for Wet H2S environment (Hardness)
	Impeller Type	• Because SSC is susceptible around Weld and HAZ, recommended to apply **weldless impeller**
	Impeller assembling	• To avoid high stress concentration on Impeller, better to use **keyless assembling**

Recommendations

<u>If the process contains H2S and H2O (Wet H2S) even small amount,</u>

Maintena-nce

Hardness verification

Inspection

- Recommended the **periodical hardness check** for internal wet parts of the equipment and vickers portable hardness measurement would be effective.
- Recommended **periodical Non-destructive examination** to verify hidden cracks underneath the metal surface for internal wet parts and **WFMT** (Wet Fluorescent Magnetic Particle Test) will be effective to verify cracks

End of document

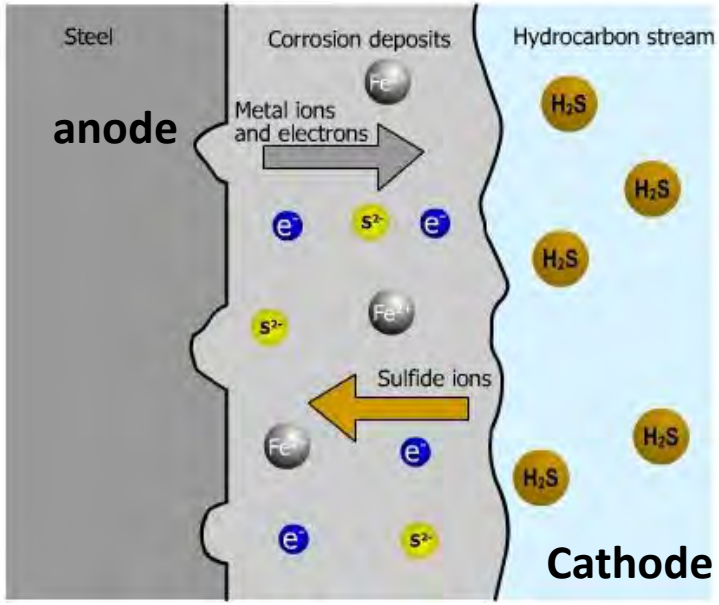
Thanks and Questions

ACKNOWLEDGEMENTS
This work has been encouraged by the Korea Rotating Machinery Engineers Association,(KRMEA).
The authors are grateful for the encouragement

Appendix : Step of Sulfide Stress Cracking

Step1. Surface corrosion : Generation of Hydrogen

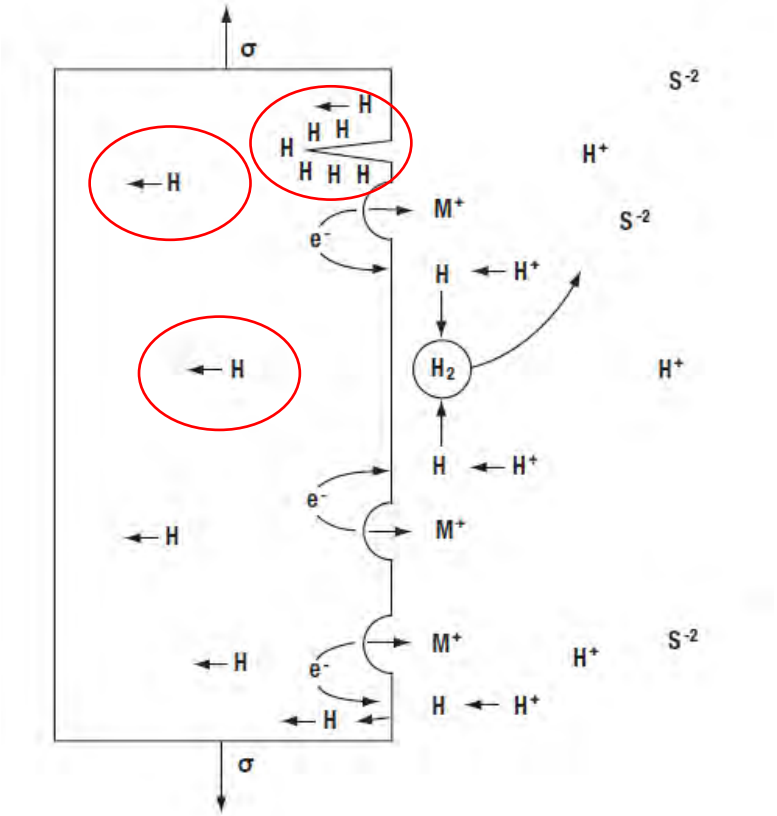
At the anode	$F \leftrightarrow Fe^{2+} + 2e$
At the cathode	$HS^+ + H_2O \leftrightarrow H^+ + S^- + H_2O$ $H_2S + H_2O \leftrightarrow H^+ + HS^- + H_2O$
Product Combination	$2e + 2H^+ + Fe^{2+} + S^- \leftrightarrow 2H^0 + FeS$
Net reaction	$Fe + H_2S \leftrightarrow FeS + 2H^0$



- *More H2S concentration, more generation of hydrogen atom*
- *More susceptible at atmospheric temperature or below 82 ℃*

Appendix : Step of Sulfide Stress Cracking

Step2. Hydrogen atom diffusion



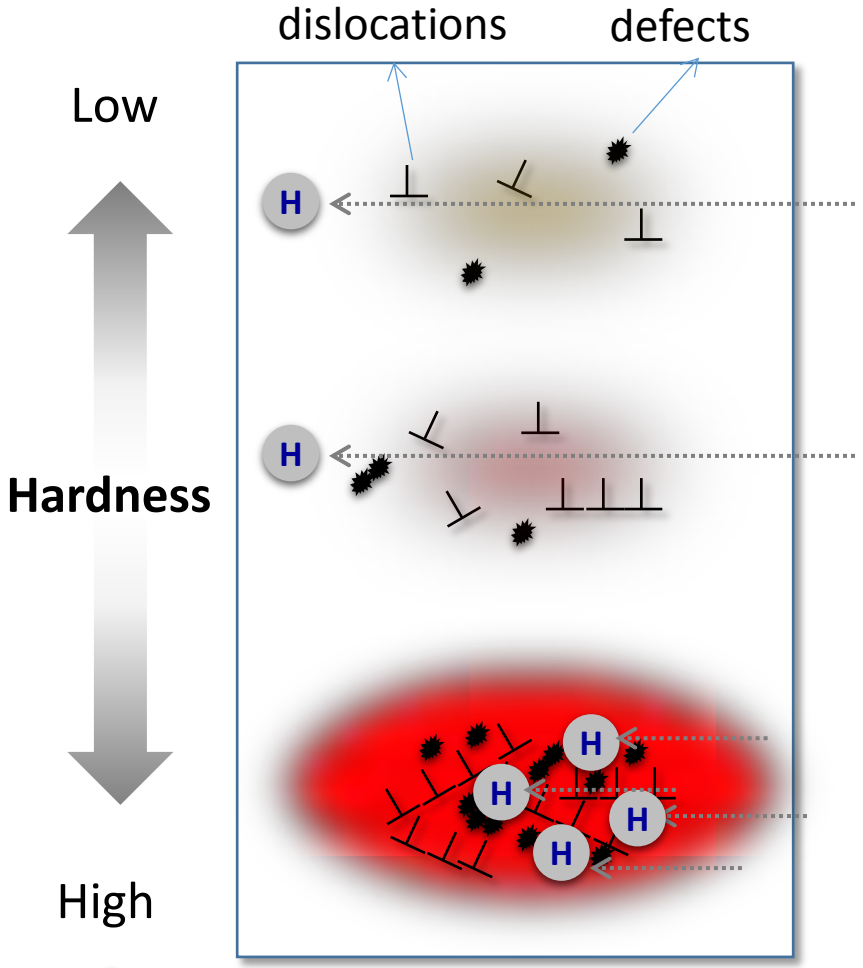
Hydrogen which is generated from corrosion reaction can diffuse to metal matrix because it is the smallest atom.

Most of hydrogen atom is passed through metal matrix.

- *Lower pH, higher diffusion rate : due to reduced recombination of hydrogen ion*

Appendix : Step of Sulfide Stress Cracking

Step3. Hydrogen atom collecting : Embrittlement



High Hardness area

= High residual stress

= Many of defects and dislocation (distortion of micro structure)

※ Normally hundreds millions of defects and dislocations is in a cubic centimeter of metal

Defects and dislocation

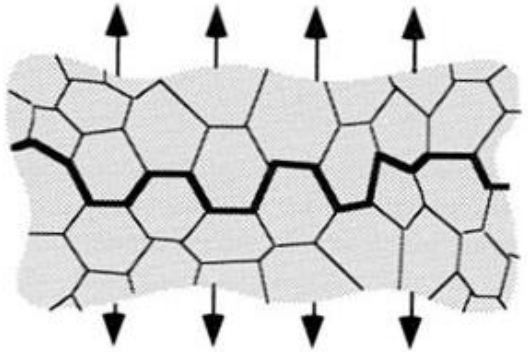
- Interrupt the diffusion of hydrogen atom
- Hydrogen atom is collected and trapped in high hardness area

As a result metal is more stressed by hydrogen atom and becoming more embrittled

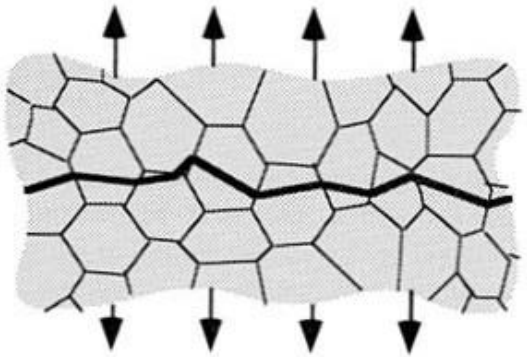
Appendix : Step of Sulfide Stress Cracking

Step4. Propagation of crack

Inter-granular crack



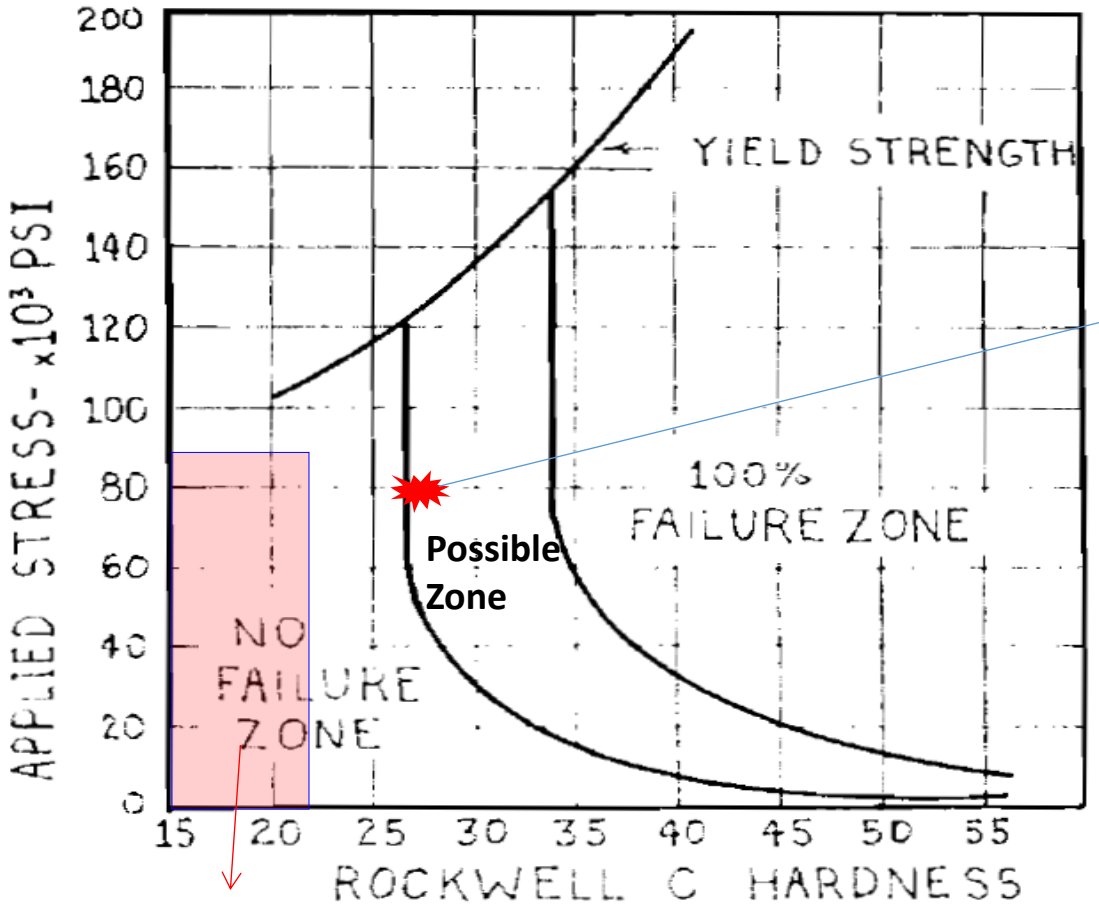
vs



Trans-granular crack

- Most of defects and dislocations in the metal is located around grain boundary. So grain boundary is more embrittled as more hydrogen atom collected.
- As a result, the crack from sulfide stress cracking mechanism is propagated along with grain boundary.

Appendix. SSC Threshold



Case 1 material hardness

Possible Zone

API Limit Zone (Failure Free Zone)

- For AISI4140
- Test result in the condition of H2O+H2S 40℃, 250 psi

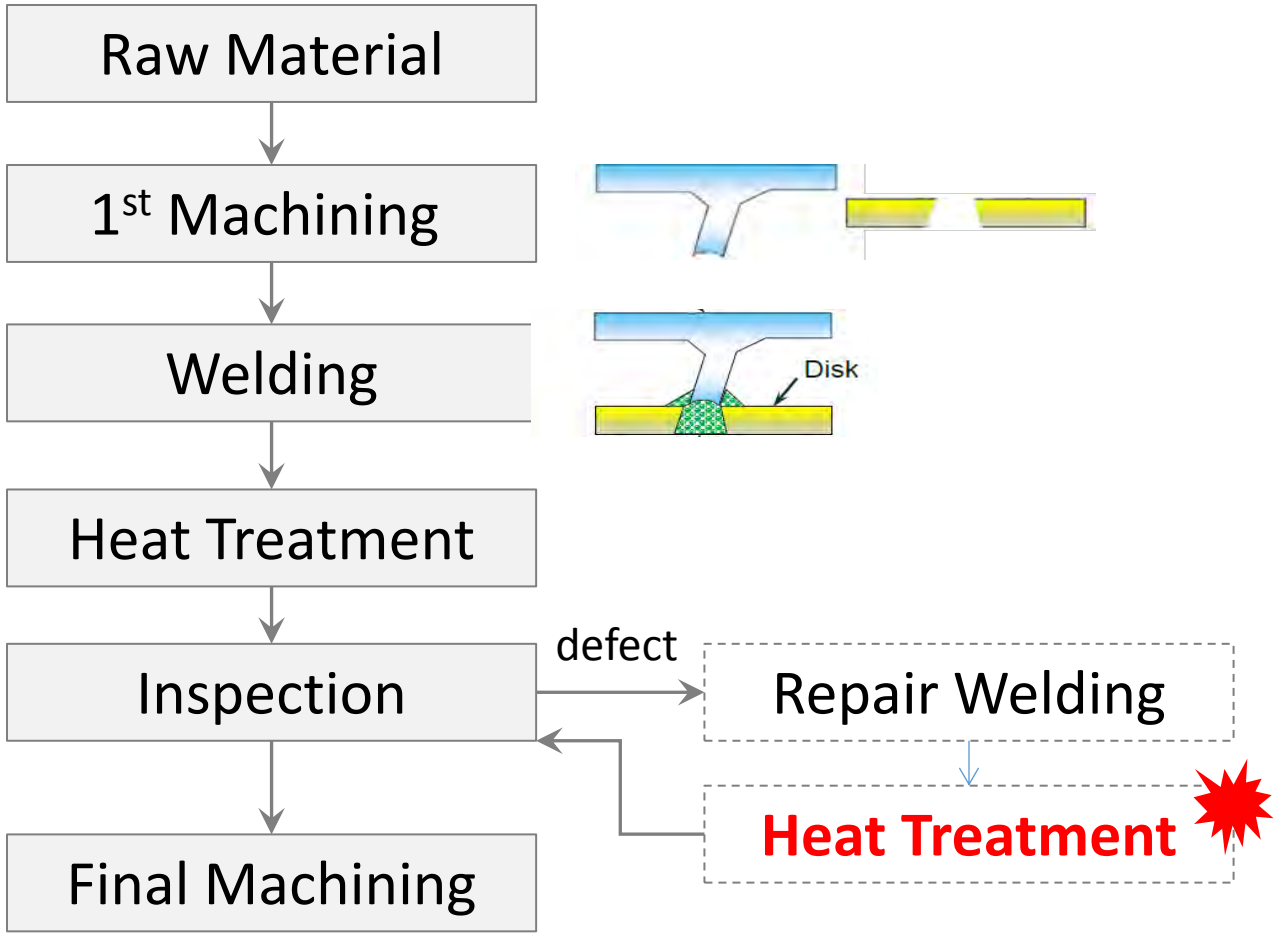
Appendix. H2S Damages

	SSC	Blistering	HIC
Hardness	As NACE standard (ex. under 200HB for C.S.)	No effect	
PWHT	Possible to reduce	No effect	
Location	Weld & HAZ	All where discontinuity like micro Fissure	
Inspection	MT(PT), UT	UT	
H_2S amount	More appearance as H2S amount increases		

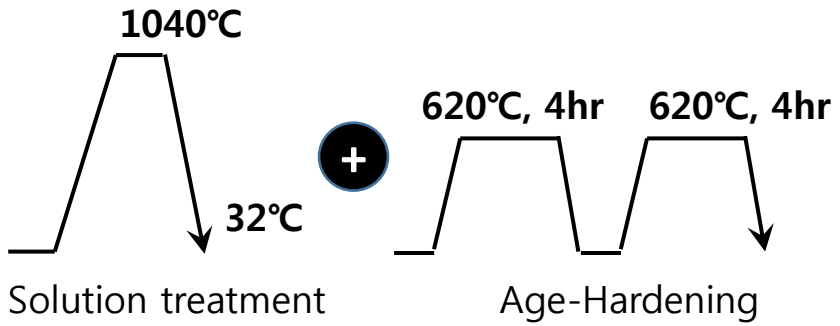
Appendix. Hydrogen embrittlement

Damage \ Factor	High Temperature	Low Temperature	High hydrogen partial pressure	Wet H2S	Hardness	Non-metal filers	Stress
High Temperature Hydrogen Attack	◈		◈				
Hydrogen Assisted Crack	◈		◈		◈		◈
Hydrogen Embrittlement		◈	◈		◈		◈
Sulfide Stress Corrosion Crack		◈		◈	◈		◈
Hydrogen Induced Crack		◈		◈		◈	
Delayed Crack		◈			◈		◈

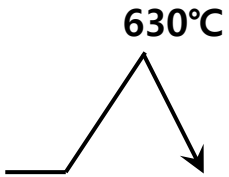
Appendix. Factory history review for Case2



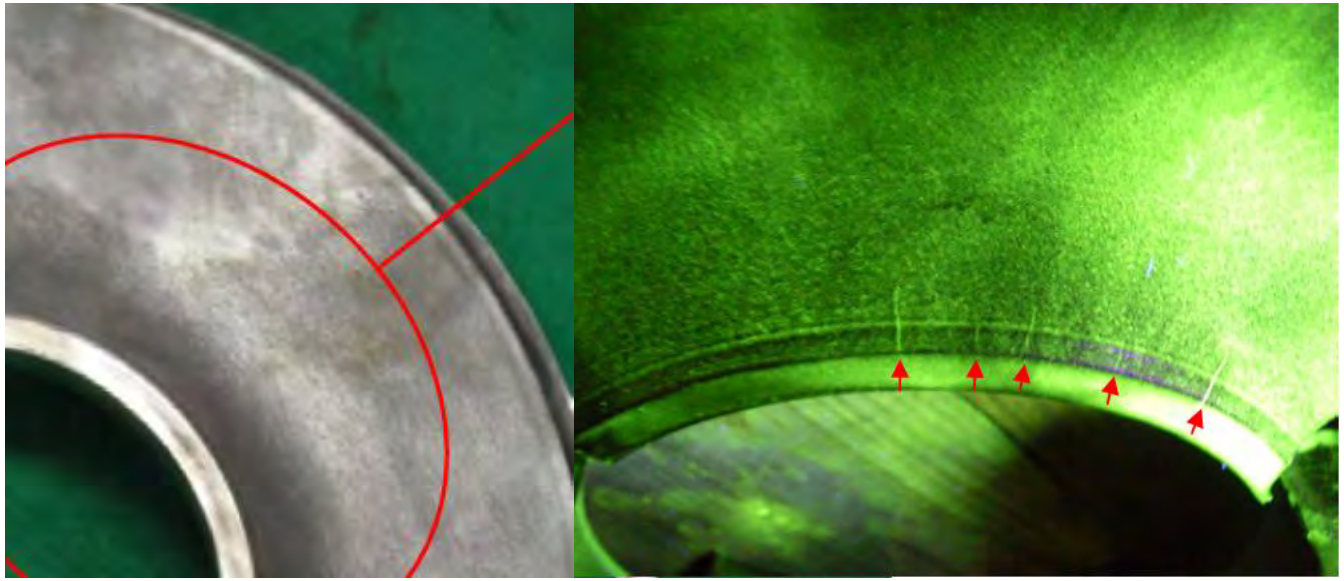
NACE Standard for 17-4PH



Actual Heat treatment after repair



Appendix. Determined crack by **WFMT**

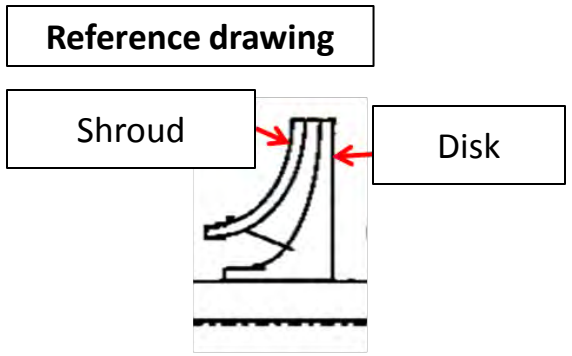


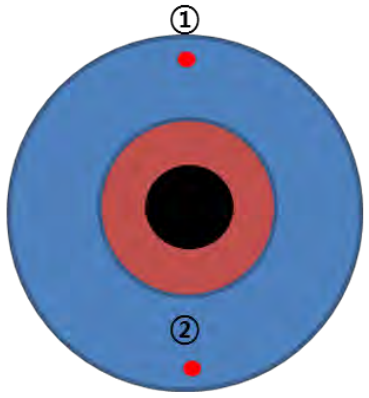
Appendix. Example of hardness verification procedure

Parts	Impeller hardness	
Inspection Point	Shroud, Disk and tip	
Method	Vickers hardness measurement	By inspection division

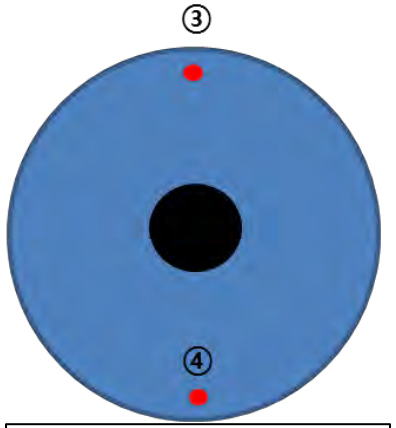
Hardness should be measured 6 points per impeller

Reference drawing

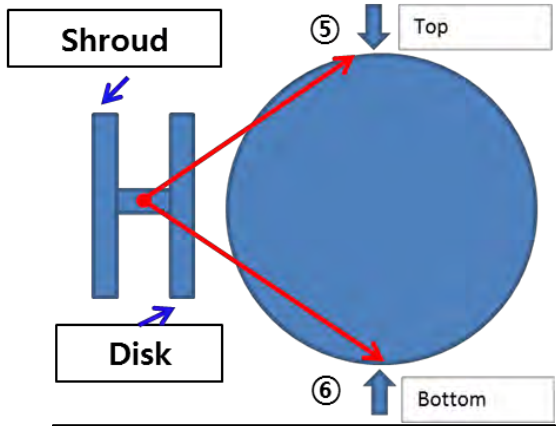




Point to measure on shroud



Point to measure on disk



Point to measure on tip

Appendix. Example of inspection procedure

Parts	Surface crack inspection for rotor	
Inspection Point	Overall surface of rotor excluding the position of bearing, prove, thrust collar	
Method	Visual inspection	By mechanical division
	WFMT	By inspection division
	PT	By inspection division

Because it's impossible to inspect the internal surface of impeller in detail, impeller eye and tip applied the magnetic field are enough to inspect If applied WFMT. Magnetic field have to be eliminated and residual magnetic field have to be under 3 Gauss after WFMT

Reference drawing