International Institute for Carbon-Neutral Energy Research

Fretting Fatigue in Hydrogen and the Effect of Impurity Addition to Hydrogen on Fretting Fatigue Properties

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3rd World Cngress on Petrochemistry and Chemical Engineering

Atlanta, USA
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KYUSHU UNIVERSITY

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World Premier International Research Center Initiative

Outline

Introduction

- Current status of hydrogen in Japan
- Fretting fatigue
- Objectives

Experimental procedure

- Test method
- Material
- Environment

Results of fretting fatigue test and discussion

- *S*-*N* curves
- Mechanisms that the FF strength in H_2 is reduced
- Effect of oxygen addition to H_2
- Mechanism

Summary

Acknowledgement

1. Introduction

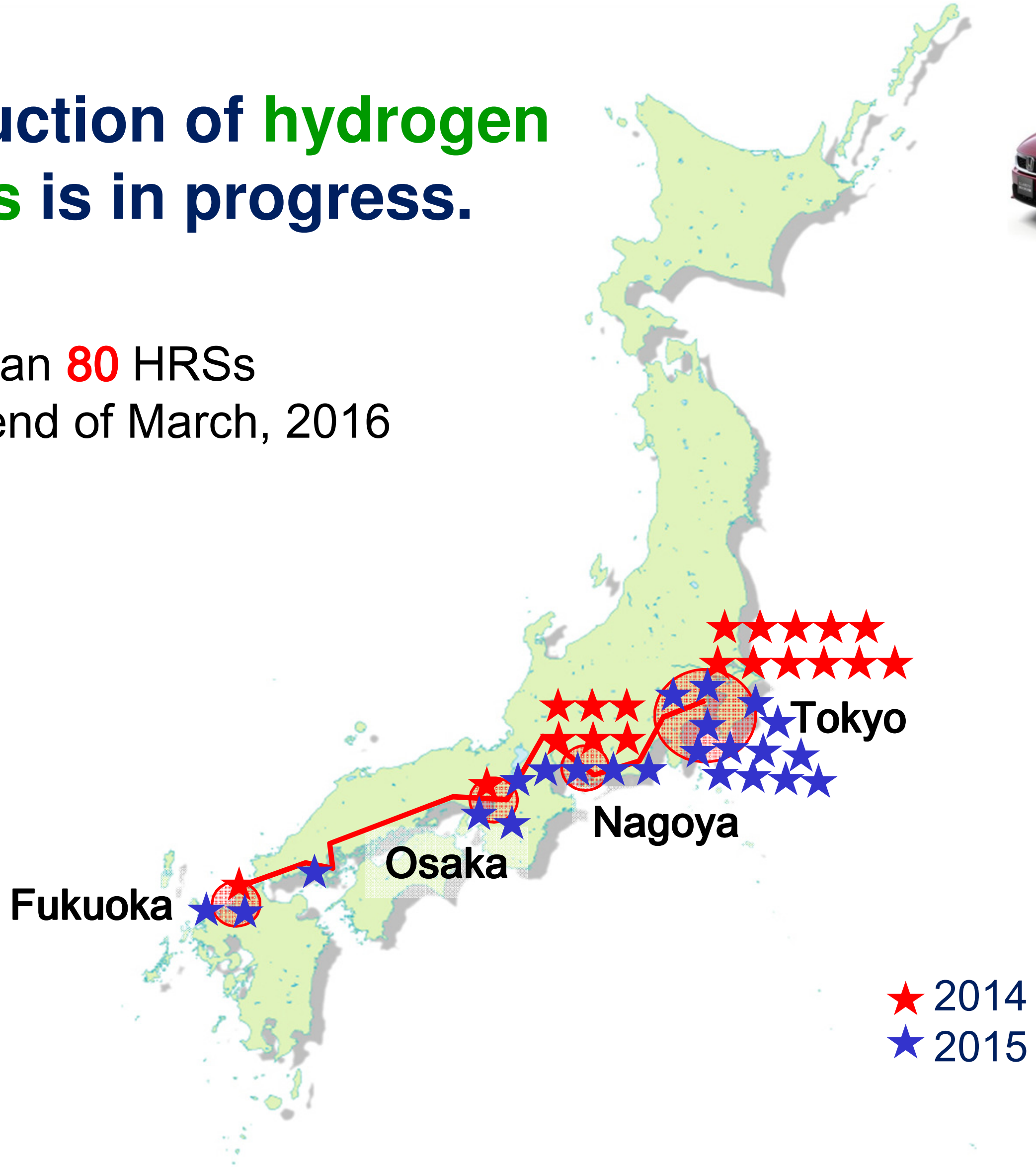
- **2014, commercialization of FCV**

Toyota FCV "MIRAI"
Toyota HP

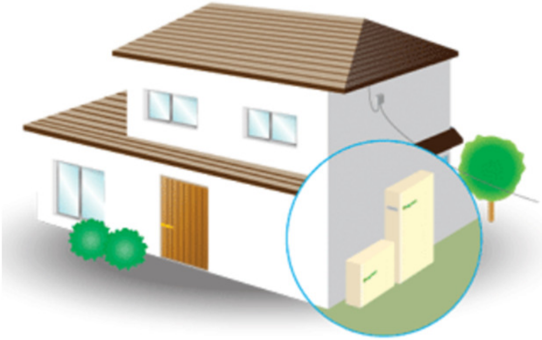
- **Construction of hydrogen stations is in progress.**

Honda FCV "CLARITY"
autoblog.com HP

More than 80 HRSs
by the end of March, 2016

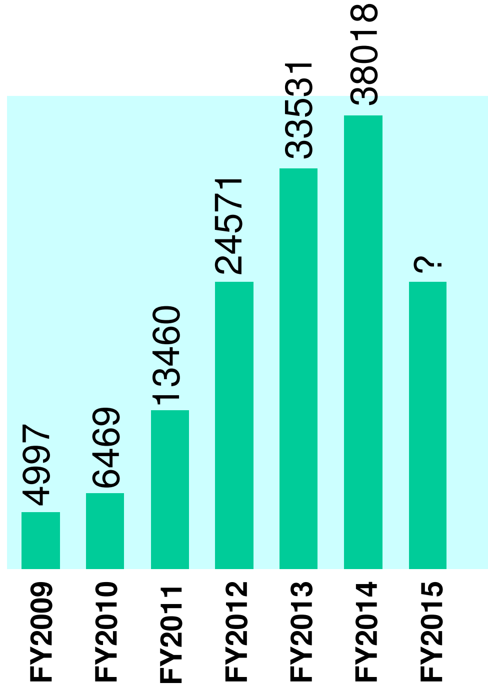


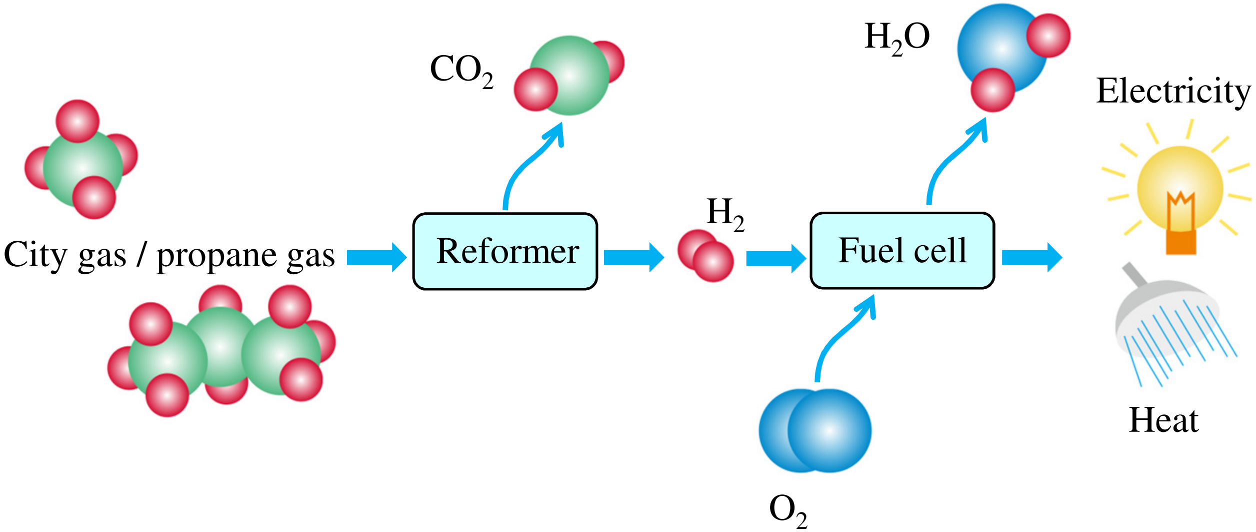
Home fuel cell system



ENE·FARM

Sales of home FC
More than **130,000**



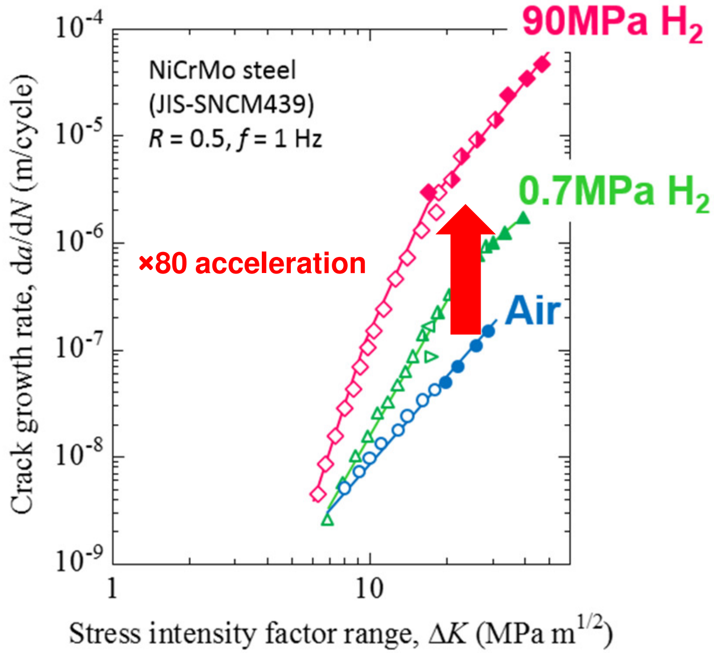


How to realize safe use of hydrogen with optimal cost

FCV !!

75MPa

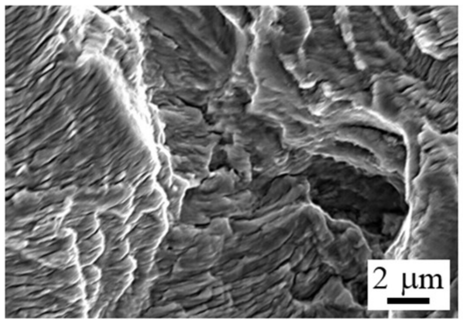
Hydrogen deteriorates materials strength.



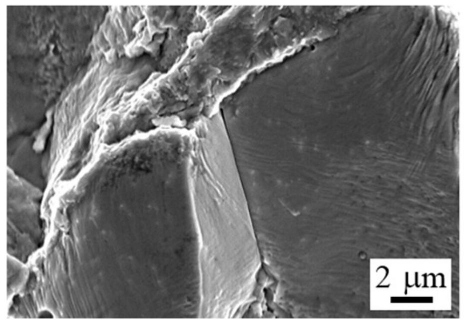
Regular gas cylinder
15MPa

S10C
σ_a=206 MPa

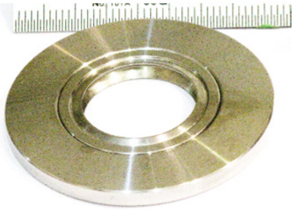
In air (N_f = 2.06×10^6)



In H_2(N_f = 2.94×10^5)

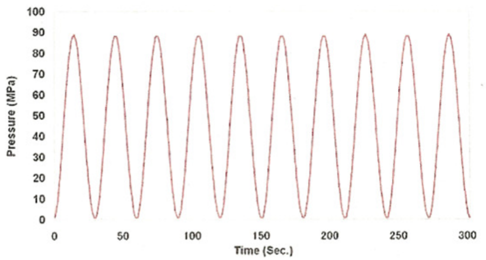


Fretting in 100MPa hydrogen packing

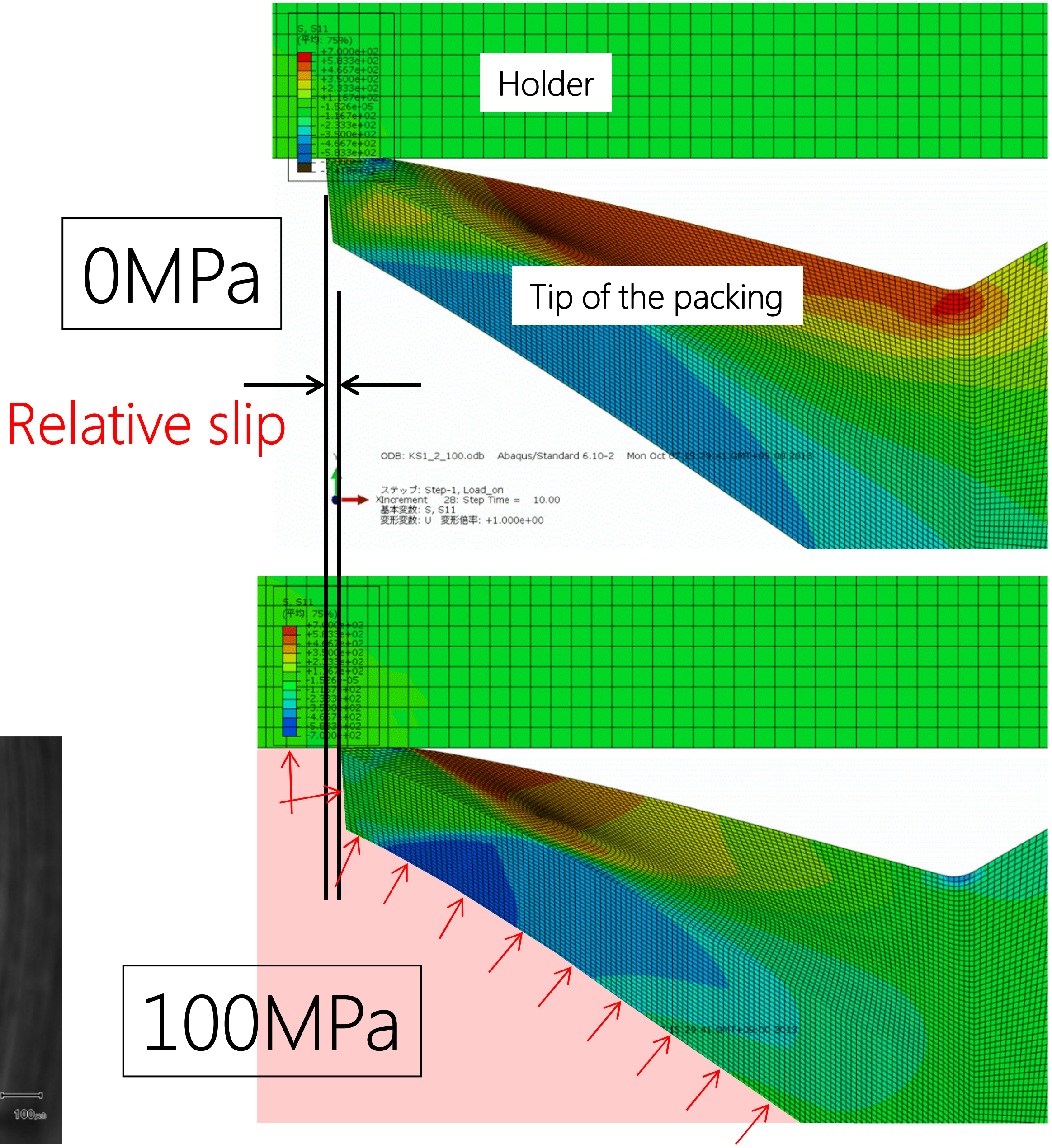


TOKi Engineering Hydroblocker®

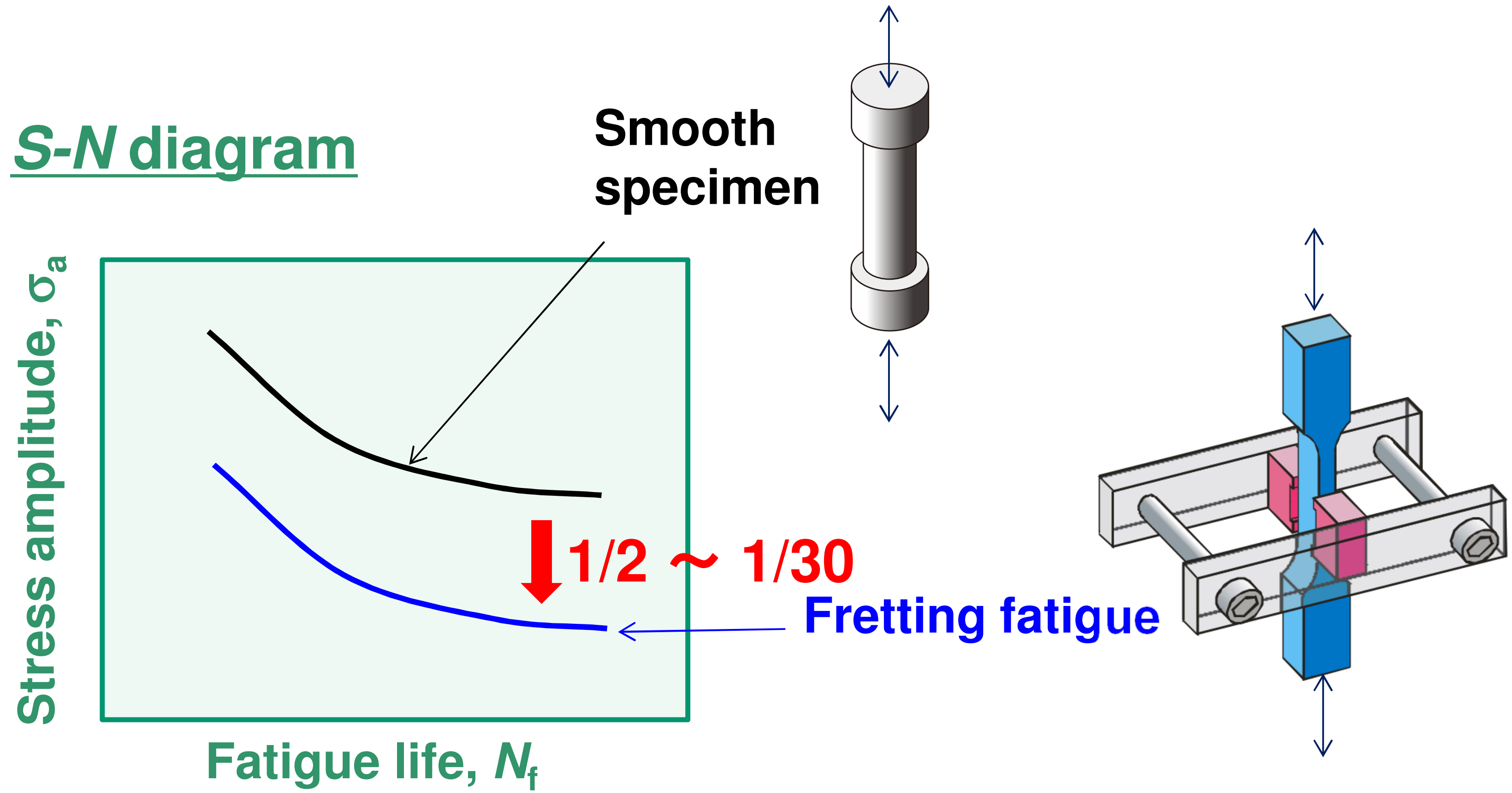
H_2 gas pressure cycling test

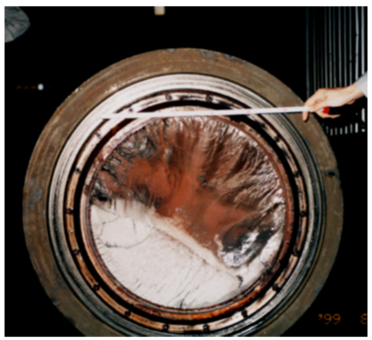


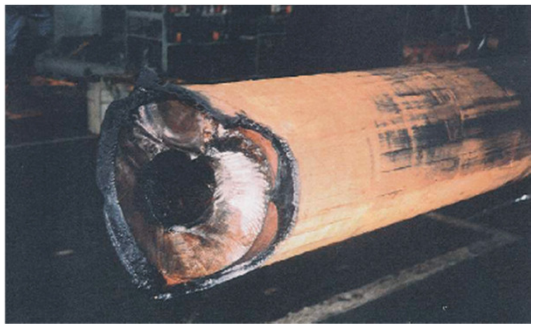
Fretting wear



Reduction in fatigue strength due to fretting

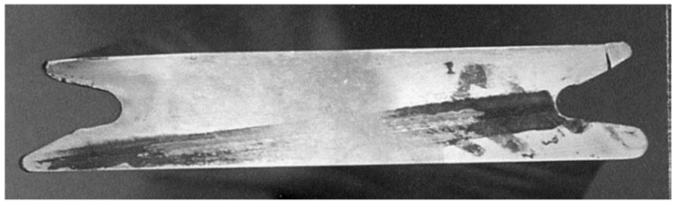






Fretting fatigue

major concerns in the design

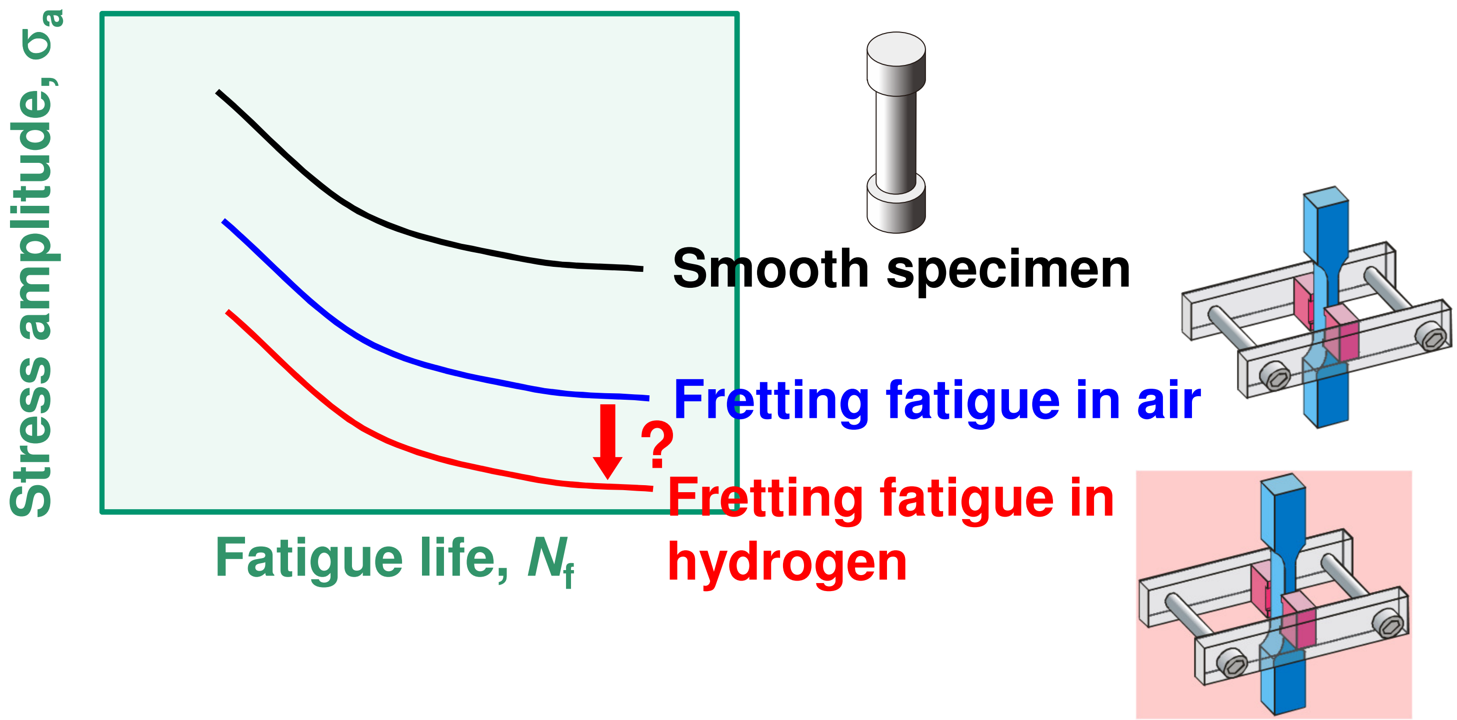


Objectives of the research on FF

Fretting fatigue

Friction & wear + Metal fatigue

Hydrogen

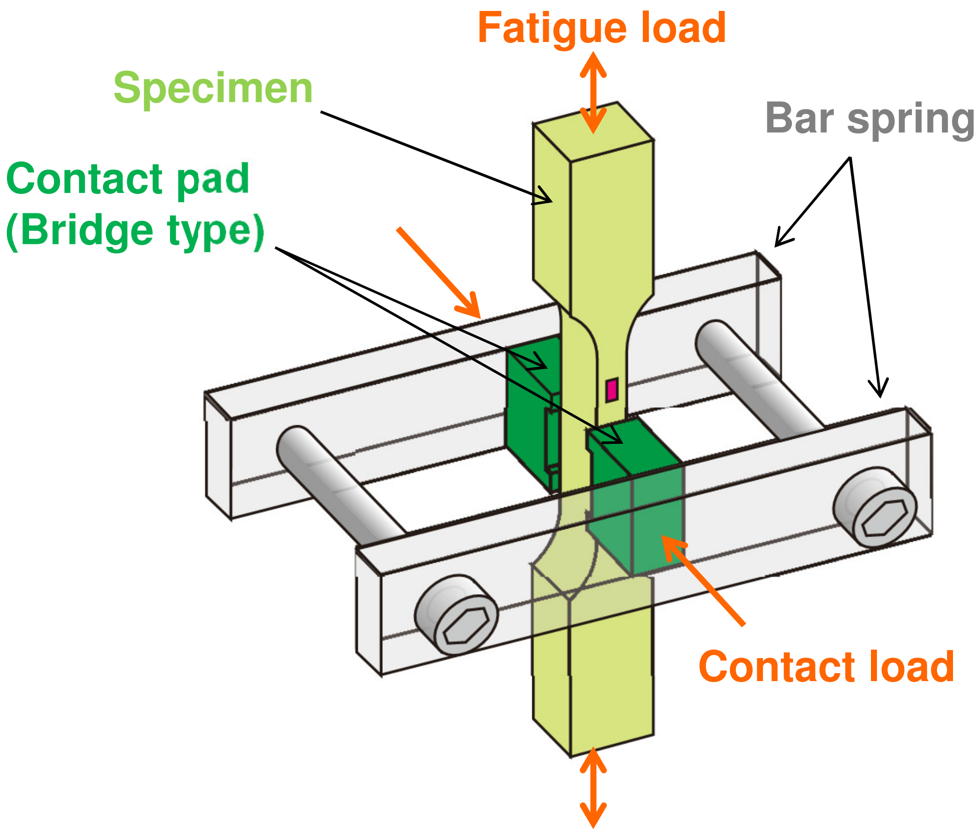


Objectives

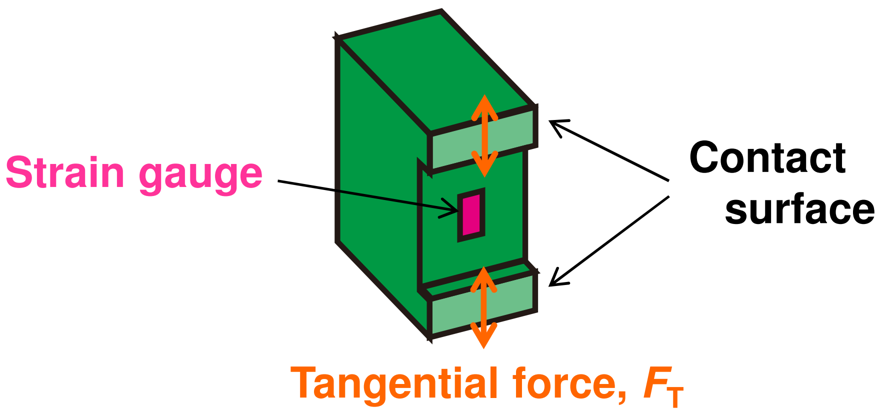
- To characterize the effect of hydrogen on fretting fatigue strength
- To elucidate the mechanisms that cause the reduction in the fretting fatigue strength
- To clarify the effect of impurities contained in hydrogen.

2. Experimental procedure

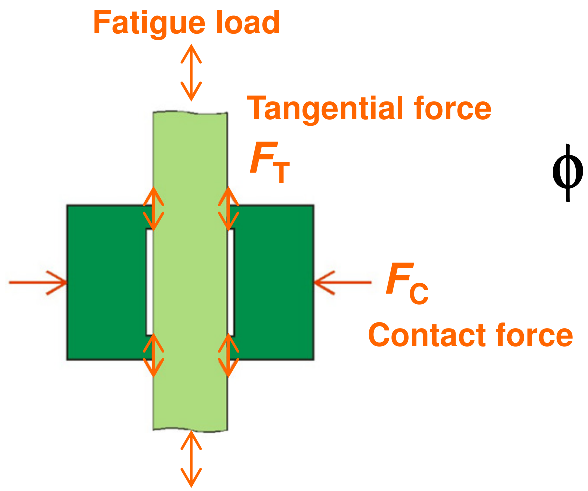
Fretting fatigue test method



Contact pressure:
p_c = 100MPa
Stress ratio:
R = -1
Loading frequency:
f = 20Hz



Tangential force coefficient



$$\phi = \frac{F_T}{F_C}$$

Austenitic stainless steels

Chemical composition (mass %)

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
JIS SUS 304	0.06	0.51	0.92	0.033	0.004	8.08	18.8	-	Bal.
JIS SUS 316	0.05	0.49	1.31	0.030	0.027	10.22	17.0	2.04	Bal.
JIS SUS 316L	0.012	0.19	1.64	0.031	0.012	12.19	16.6	2.22	Bal.

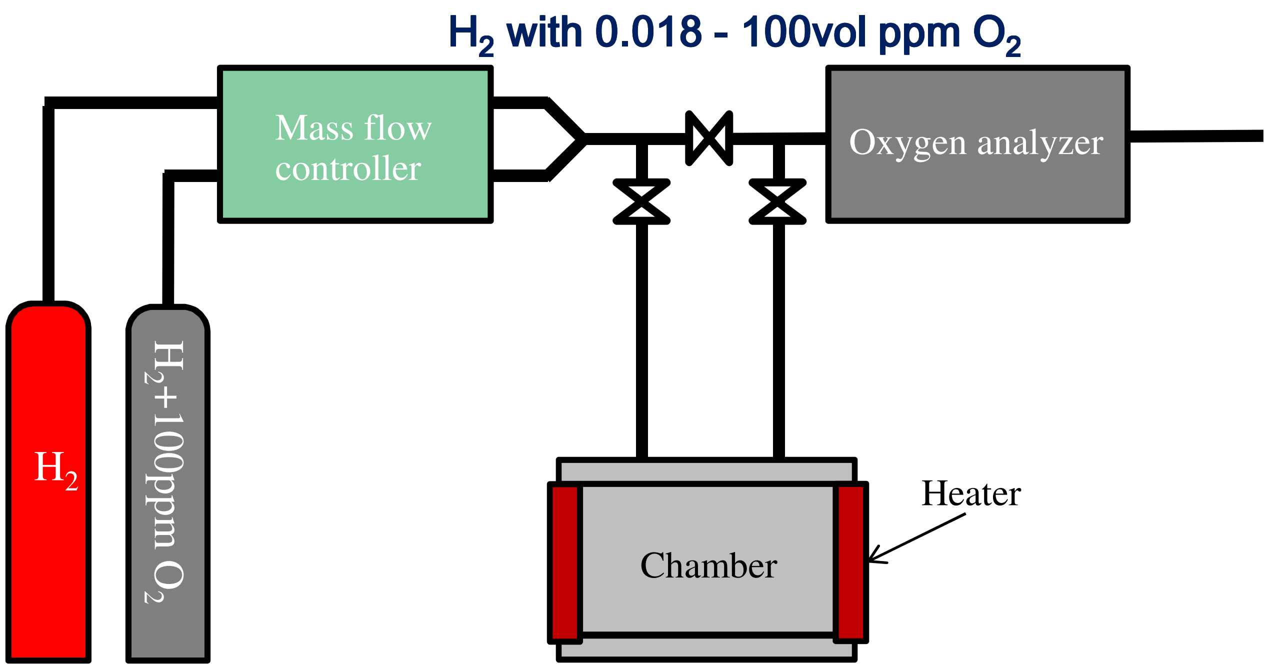
Solution heat treated:

Quenching following heating at 1303K for 3.9ks

Environment

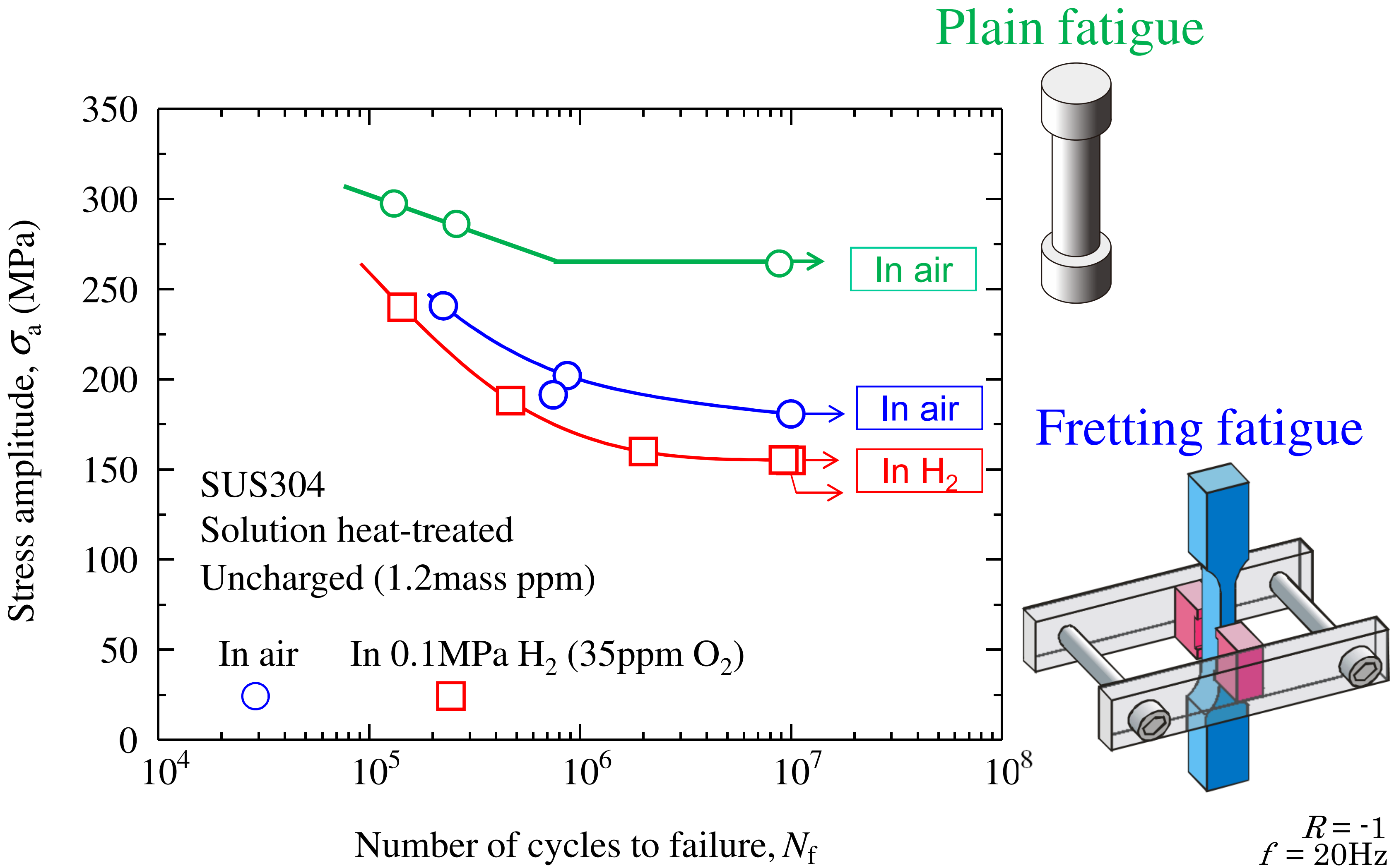
- **Laboratory air**
- **Hydrogen**
  0.018 ppm O_2,
  0.1MPa in gauge pressure,
- **Hydrogen – oxygen mixture**
  5, 35 and 100 ppm O_2,
  0.1MPa in gauge pressure,

Ambient temperature



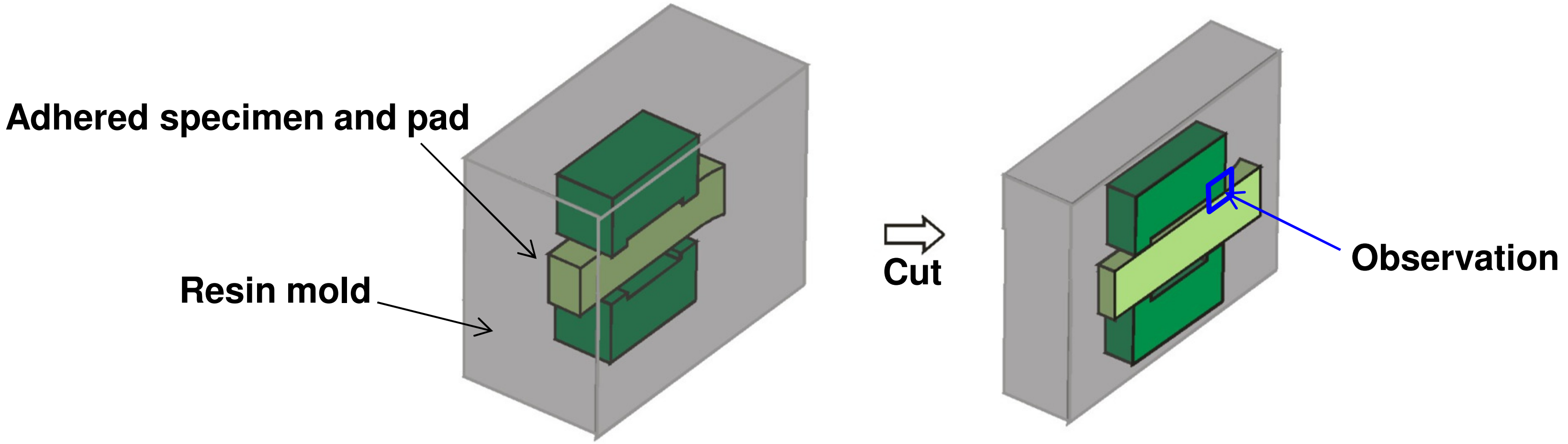
3. Result and discussion

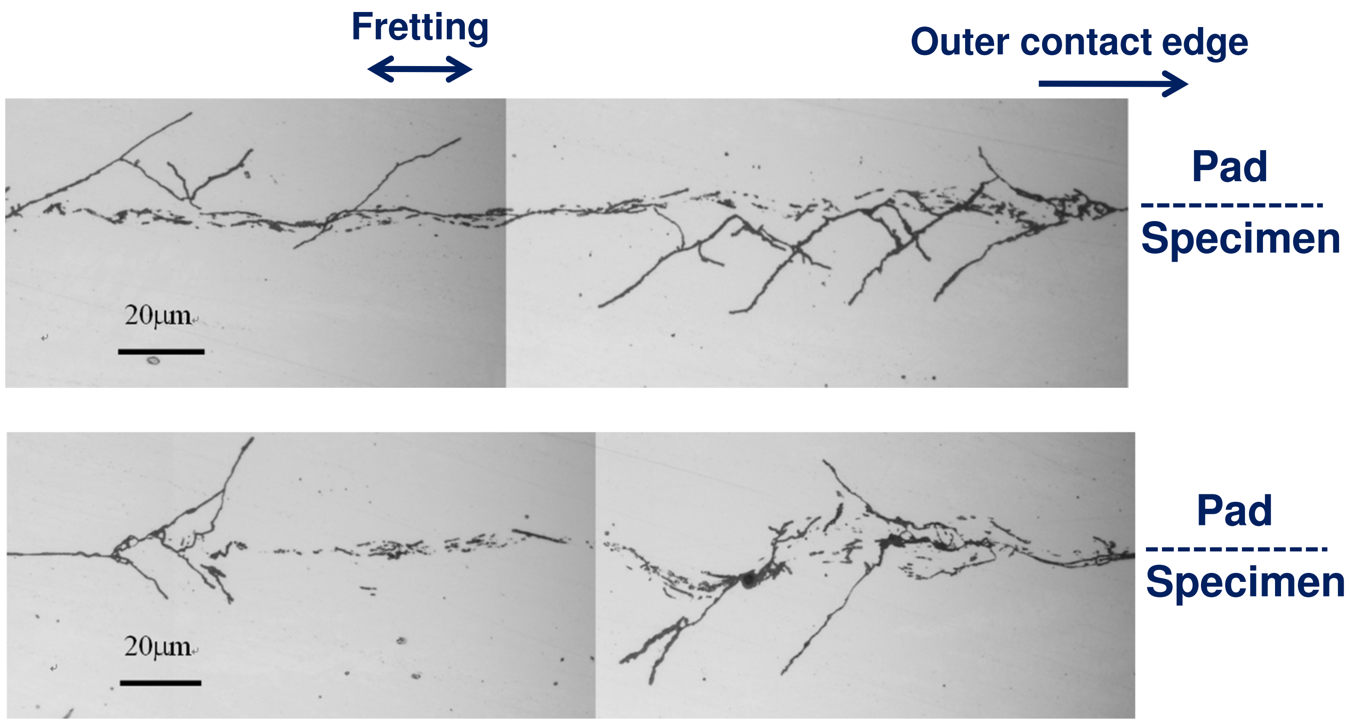
Effect of hydrogen environment



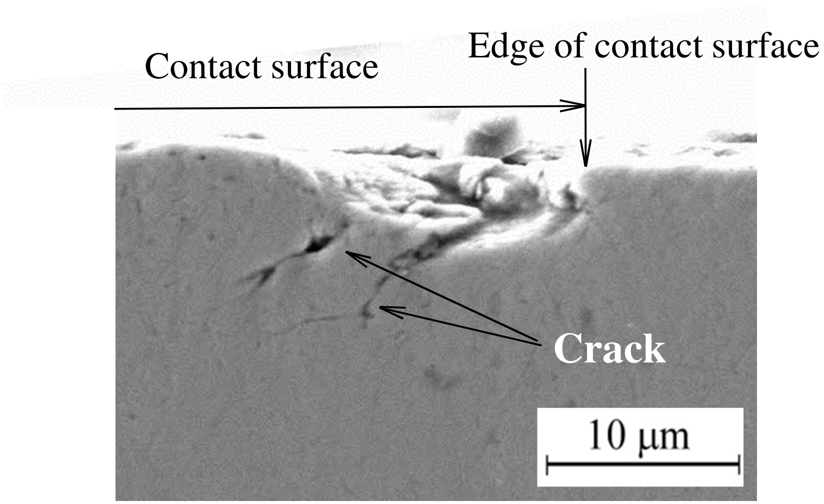
R = -1
f = 20Hz
p_c = 100MPa
Surface finish: buffing

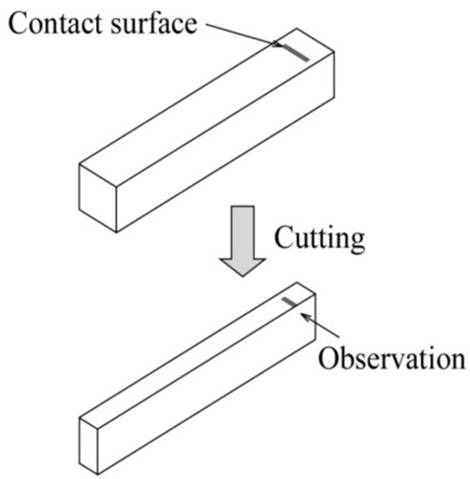
Local adhesion and small cracks during FF in H_2





Critical stress to crack initiation





Result of identification of small fretting crack initiation (At $N = 10^5$ cycles)

In air

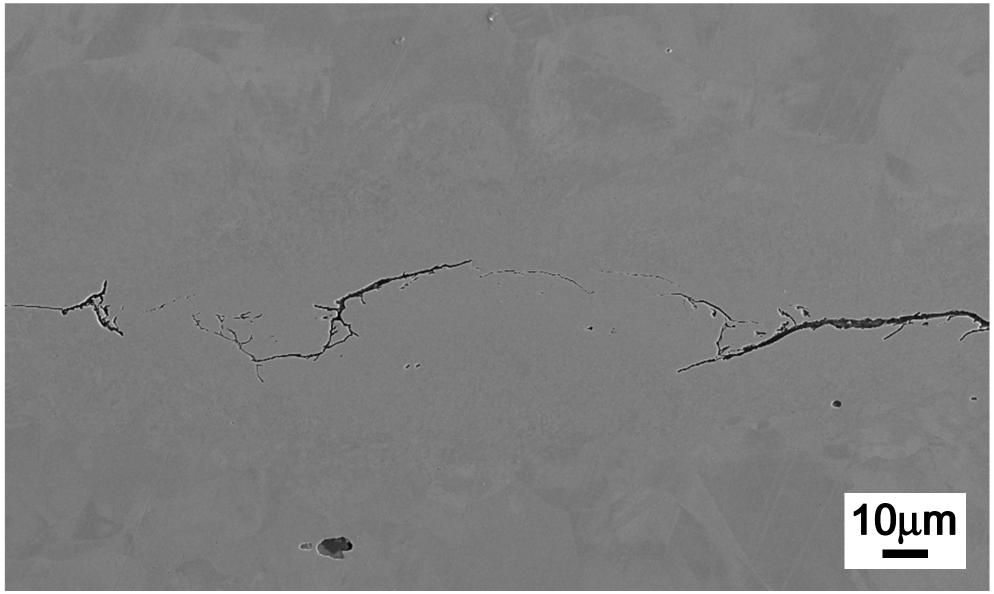
SUS304		Contact pressure , p_c (MPa)		
		25	50	100
Tangential force coefficient , ϕ	0.3	No	No	No
	0.5	No	No	No
	0.7	No	No	No

In H_2

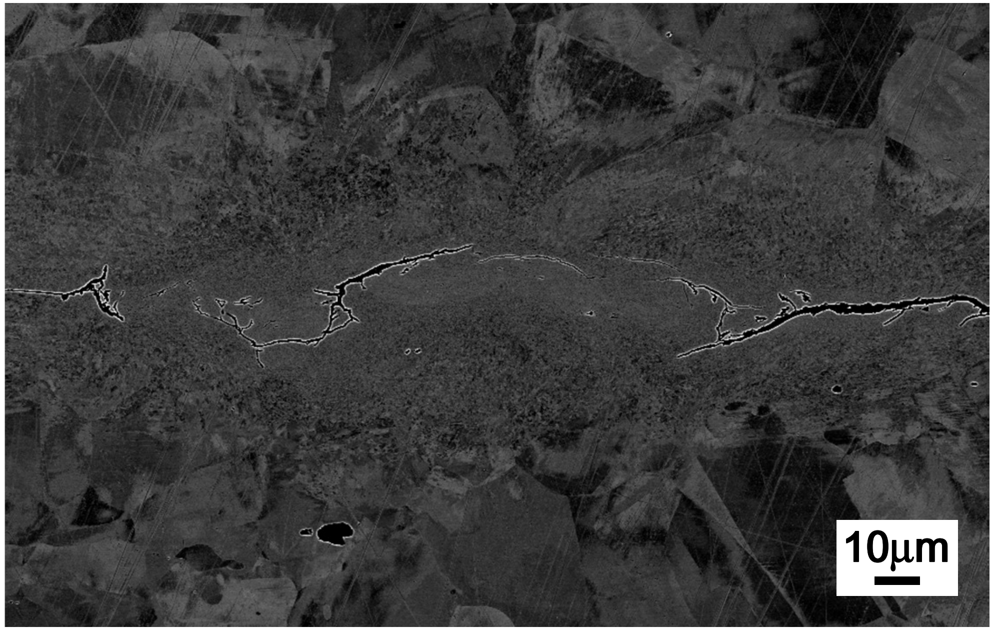
SUS304		Contact pressure , p_c (MPa)		
		25	50	100
Tangential force coefficient , ϕ	0.3	No	No	**Crack**
	0.5	No	No	**Crack**
	0.7	**Crack**	**Crack**	**Crack**

Grain refinement during FF in H_2

SUS316L
H-charged,
In H_2,
Ra = 0.008mm,
σ_a = 182MPa,
$N_f = 1.0 \times 10^6$



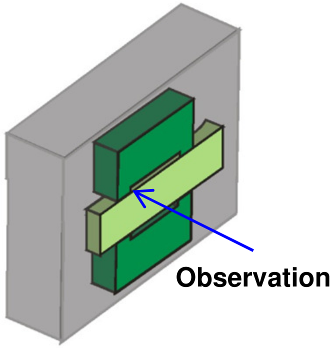
Normal SEM



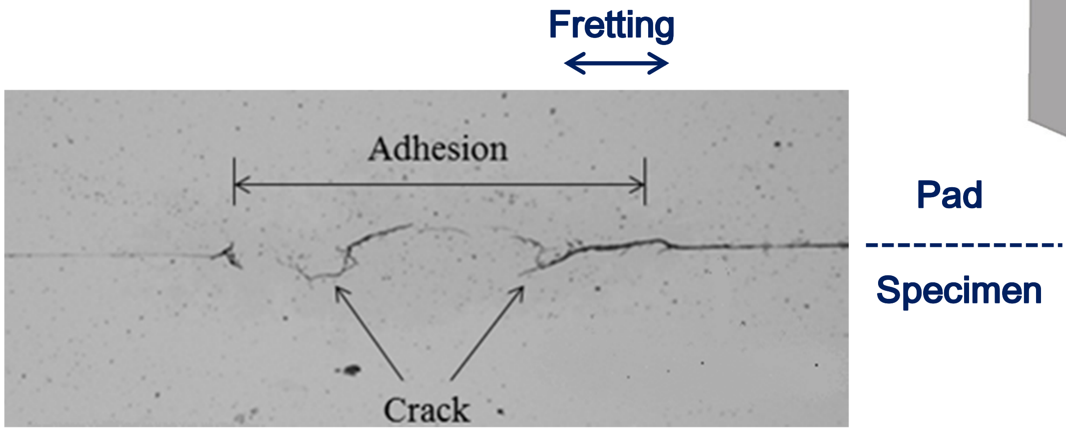
High contrast SEM

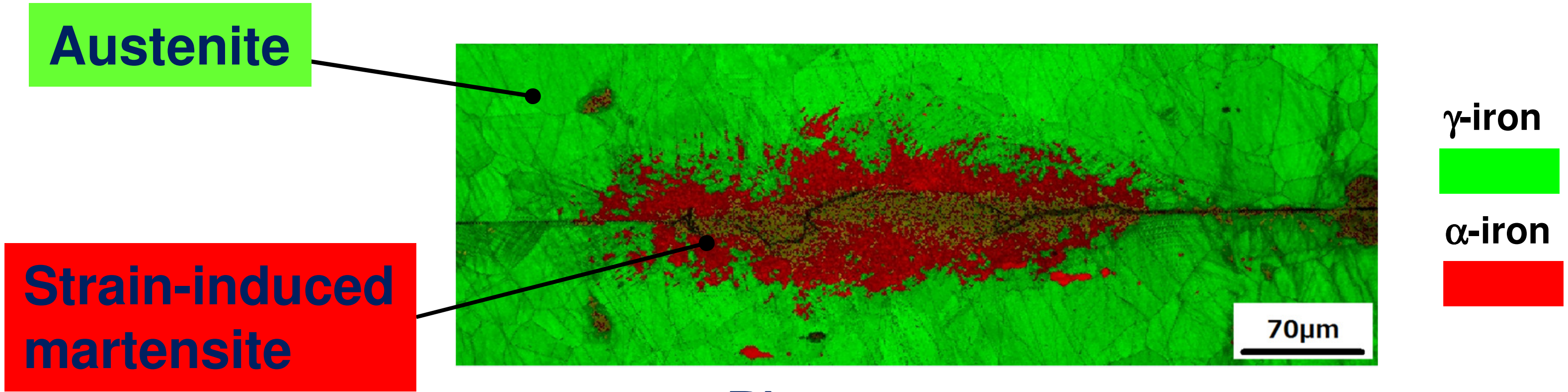
Transformation from austenite to strain-induced martensite

EBSD (Electron BackScatter Diffraction image)



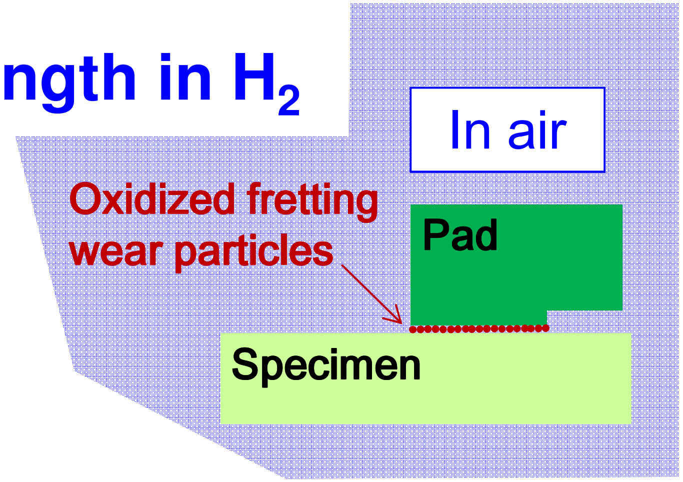
SUS316L
H-charged,
In H_2,
$Ra = 0.008$mm,
$\sigma_a = 182$MPa,
$N_f = 1.0 \times 10^6$

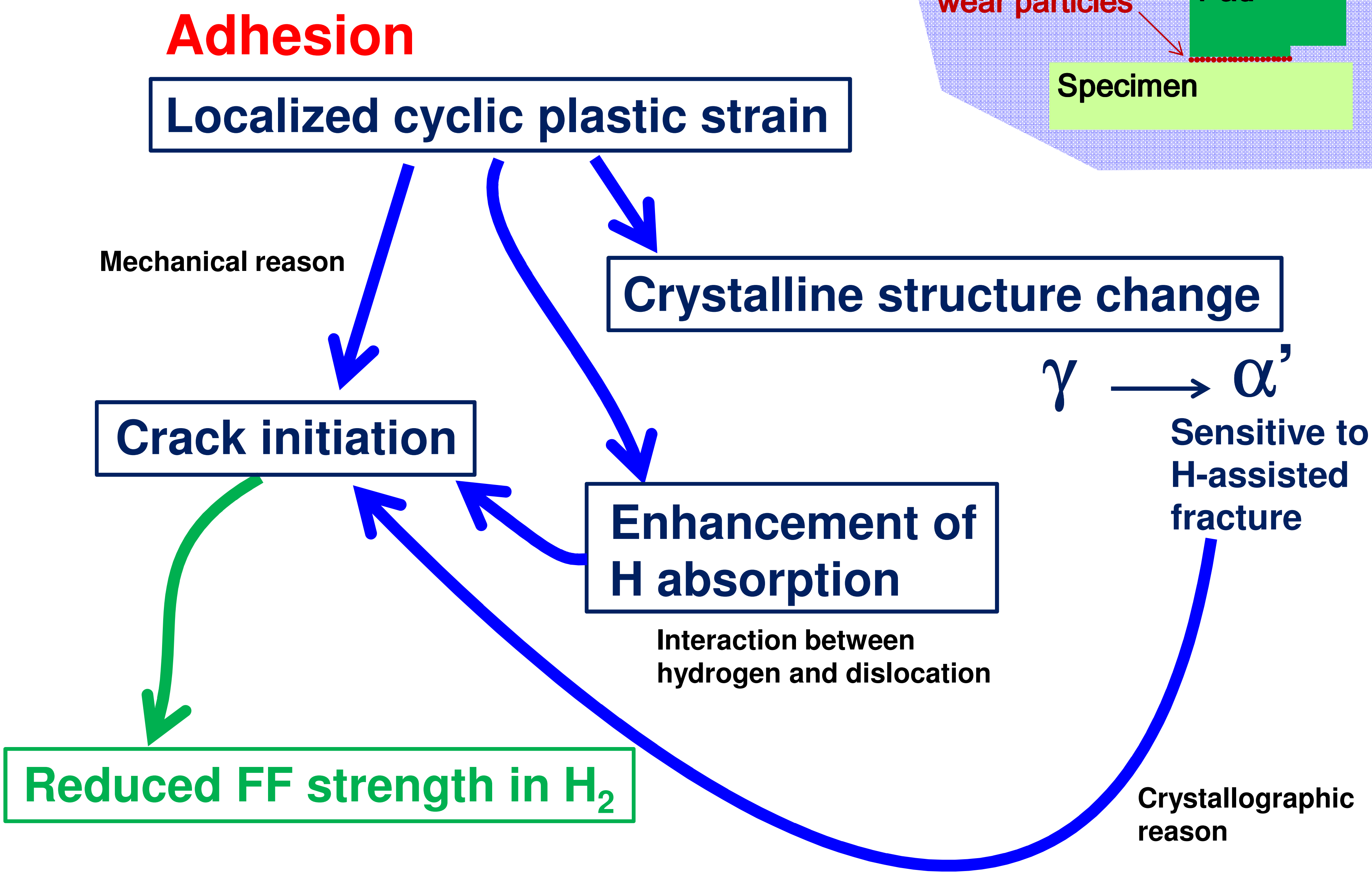




Phase map

Role of adhesion in the reduced FF strength in H_2





Purity of hydrogen for FC

Hydrogen fuel – Product specification -

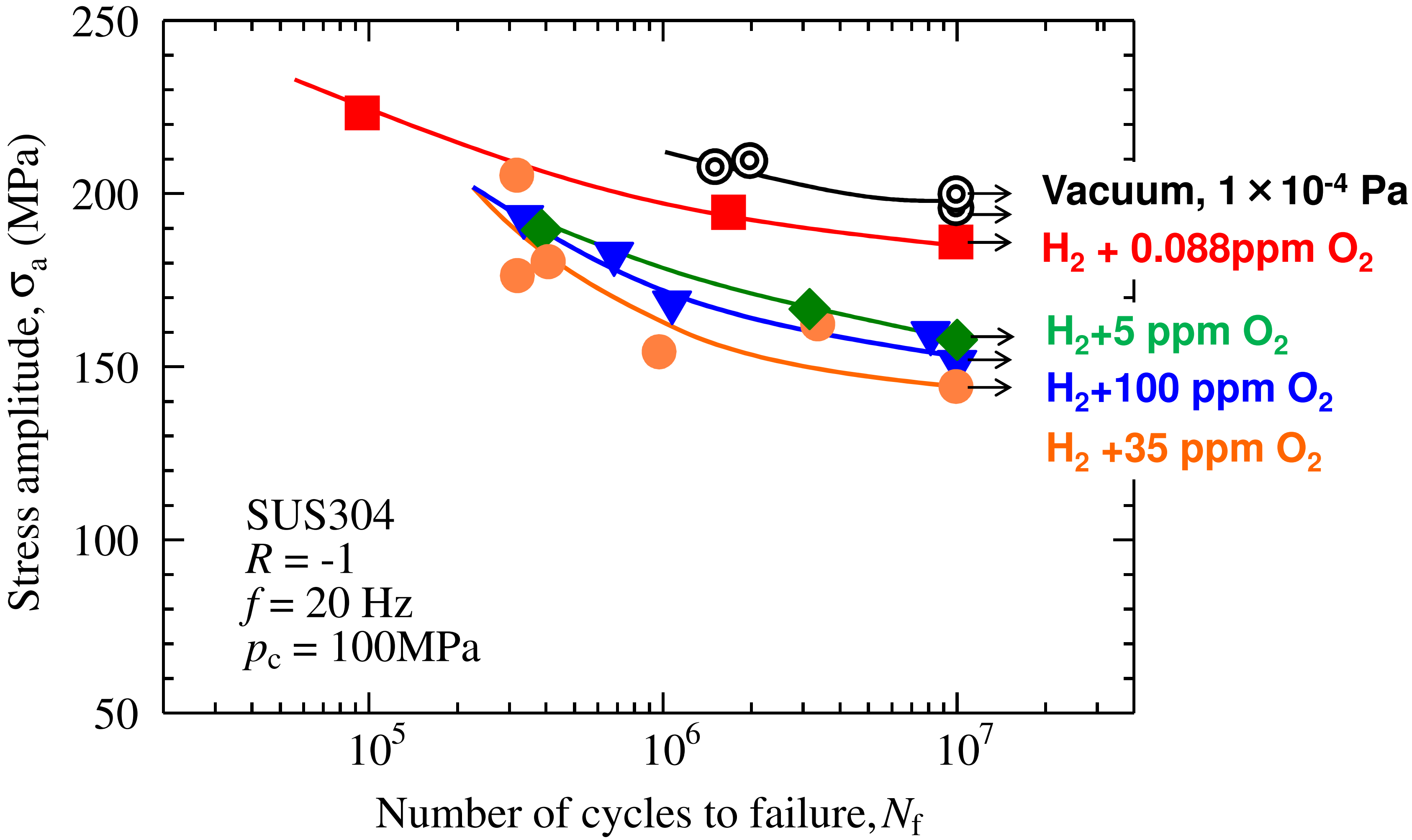
ISO 14687-2: 2012

Species	Allowable value
Hydrocarbon	< 2 ppm
H_2O	< 5 ppm
O_2	< 5 ppm
He	< 300 ppm
Ar, N_2	< 100 ppm
CO_2	< 2 ppm
CO	< 0.2 ppm
S	< 0.004 ppm
HCHO	< 0.01 ppm
HCOOH	< 0.2 ppm
NH_3	< 0.1 ppm
Halide	< 0.05 ppm
Particle	< 1 mg/kg

(1) Hydrogen contains impurities.

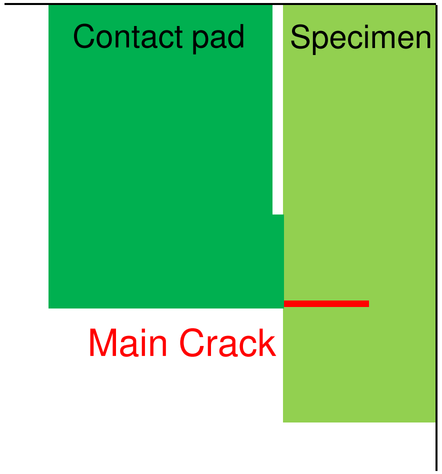
(2) Adhesion is sensitive to impurities.

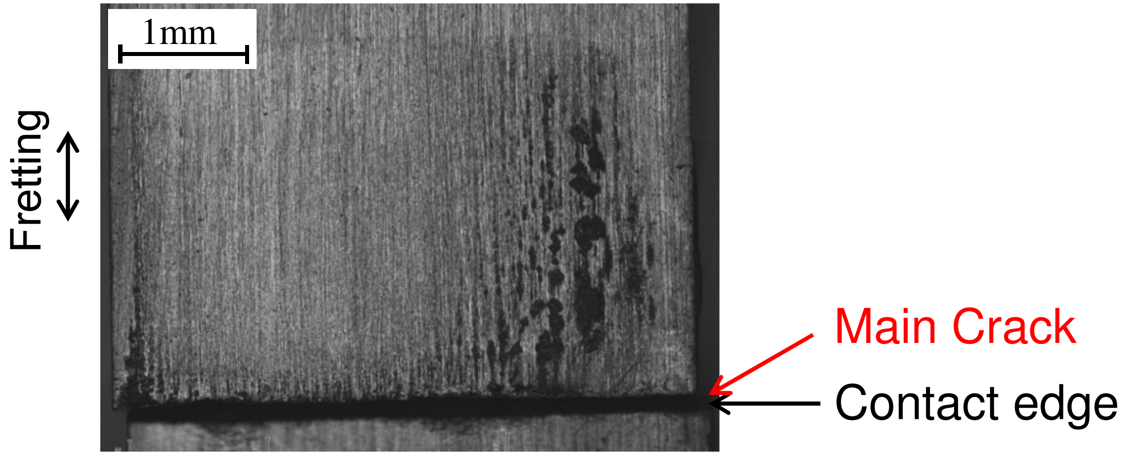
Effect of O_2 addition on FF strength in H_2



Shift of crack initiation site by the addition of O_2

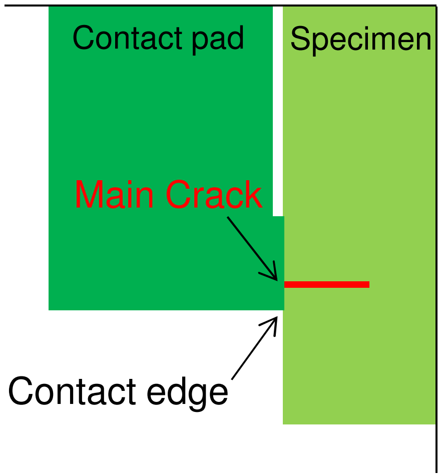
H_2 + 0.088ppm O_2

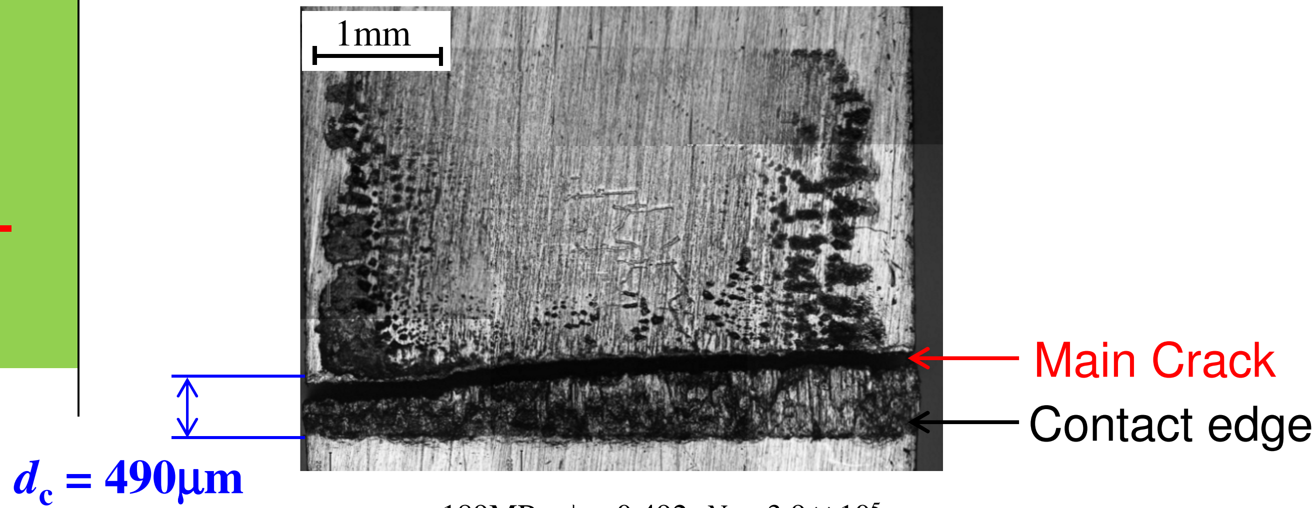




σ_a = 194MPa, ϕ = 0.478, $N_f = 1.6 \times 10^6$

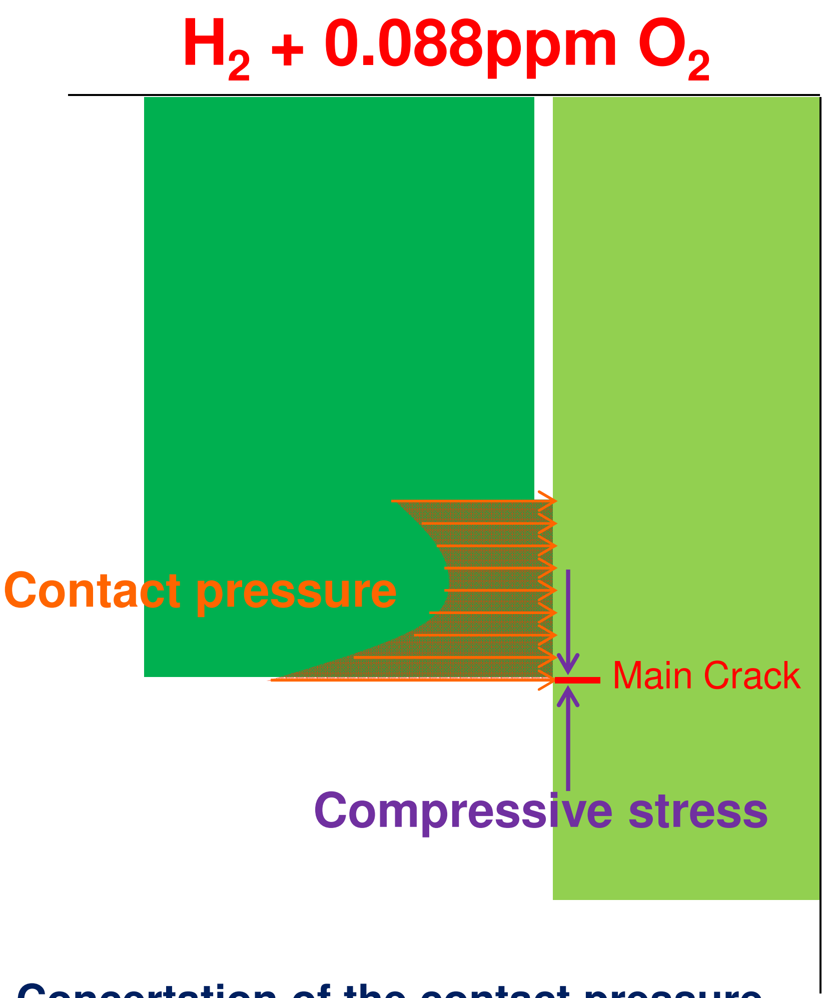
H_2+5 ppm O_2

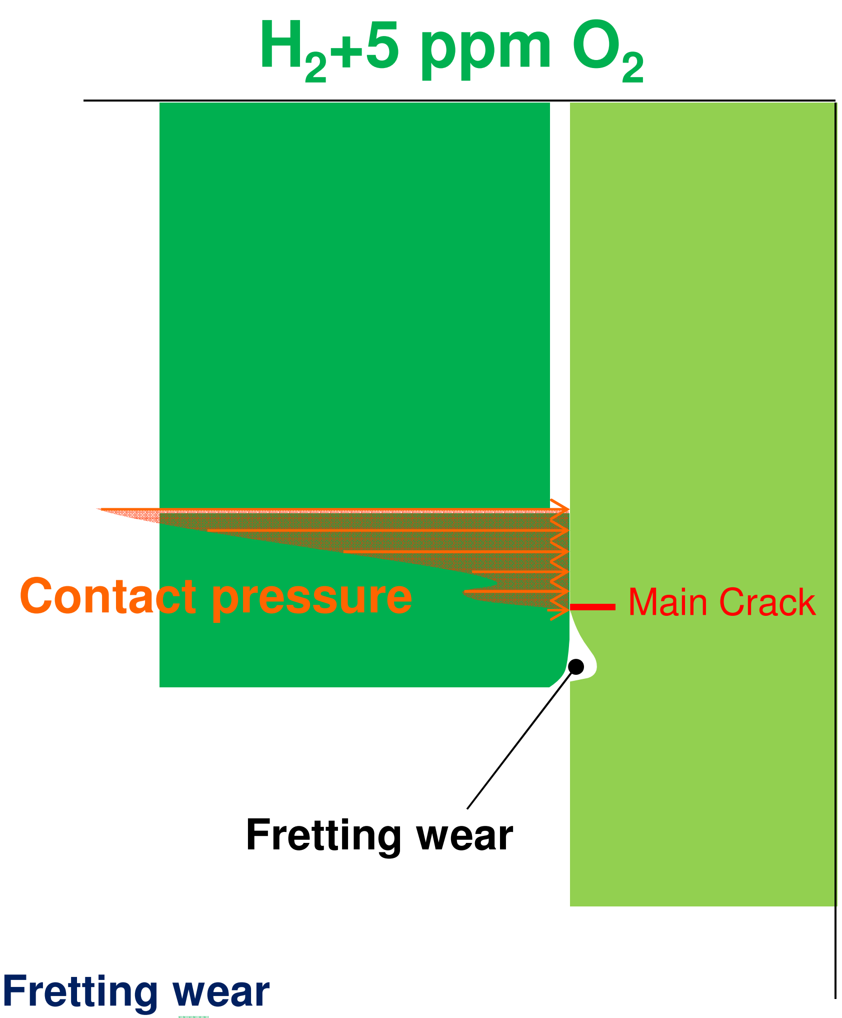




σ_a = 189MPa, ϕ = 0.492, $N_f = 3.9 \times 10^5$

Mechanism that O_2 addition reduces FF strength





Concertation of the contact pressure

Compressive stress filed

Prevention of crack growth

Higher FF strength

Fretting wear

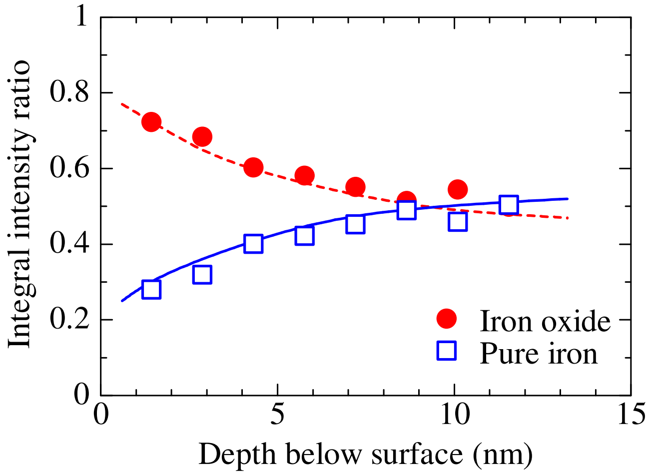
Relieve concentration of the contact pressure

No compressive stress field

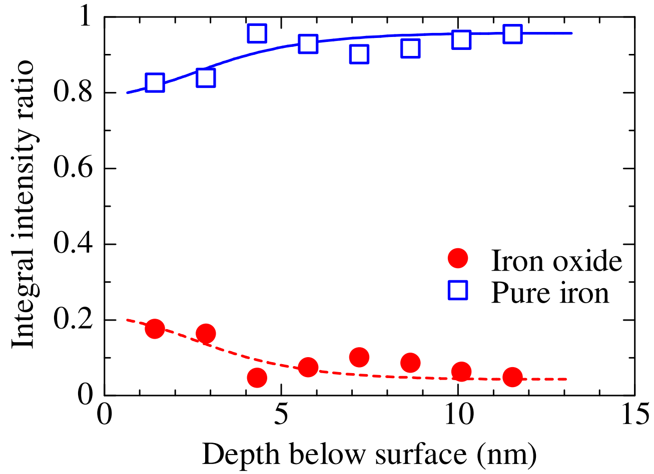
Lower FF strength

XPS analysis of fretted surface

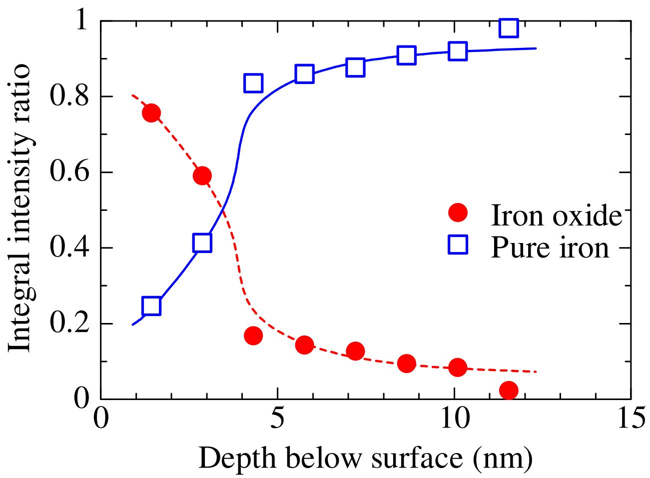
Abundance ratios of iron & iron oxide



Unfretted surface



H_2 + 0.088ppm O_2



H_2+5 ppm O_2

4. Conclusion

Fretting fatigue strength in H_2 and the effect of O_2 addition was studied.

(1) The FF strength in H_2 is significantly lower than that in air.

(2) Adhesion between the contacting surfaces occurred during FF in H_2. The adhesion causes localized severe cyclic plastic strain and transformation of crystalline structure. All these phenomena are responsible for the reduced FF strength in H_2.

(3) The addition of ppm-level O_2 drastically changed the FF strength in H_2.

(4) The addition of O_2 changed fretting wear behavior. It resulted change in the stress conditions at the contact edge. As the result, the FF strength in H_2 was reduced.

Acknowledgement

Most part of this study was carried out in collaboration with Air Liquide, France and Air Liquide Japan.

Thank you for your attention.

Hydrogen campus of Kyushu University

Professor Petros Sofronis, Director

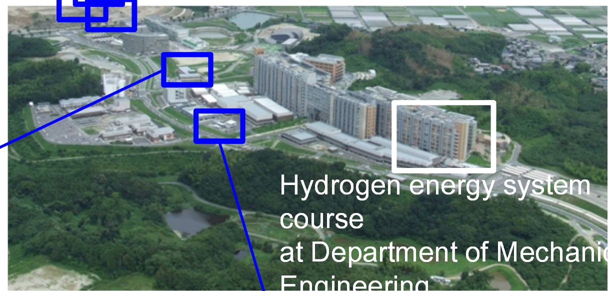
WPI-I2CNER

Establish sustainable society

CO2 reduction, H2 production, Fuel cell, CCS, Hydrogen embrittlement, etc.

SOFC + MGT
Power generation
250kW

NEXT-FC



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HYDROGENIUS

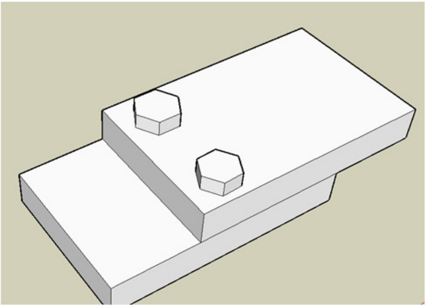
Accelerate transition to hydrogen economy

Reduce regulation, Help R&D, etc.

Hydrogen station

Field test
Advertising of hydrogen energy
Foster public acceptance

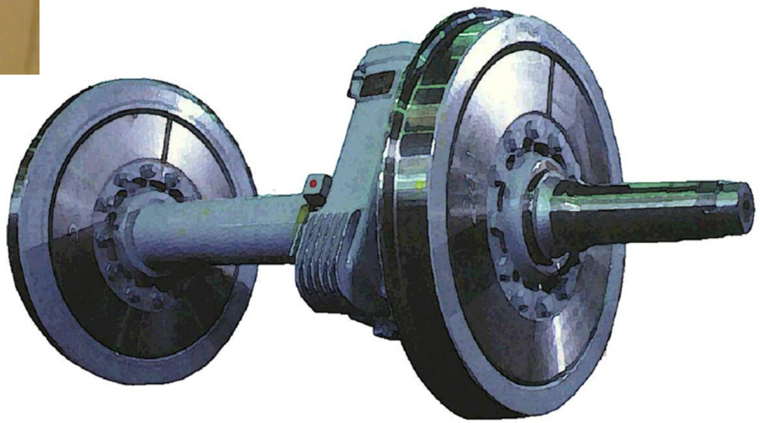
Typical components suffering from fretting fatigue

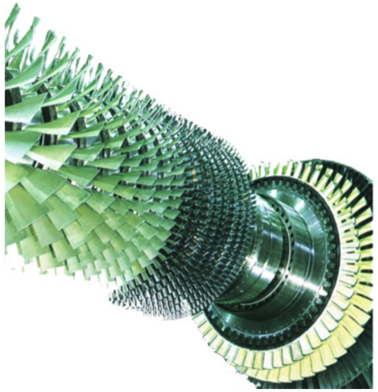


Bolted joint

Clamp

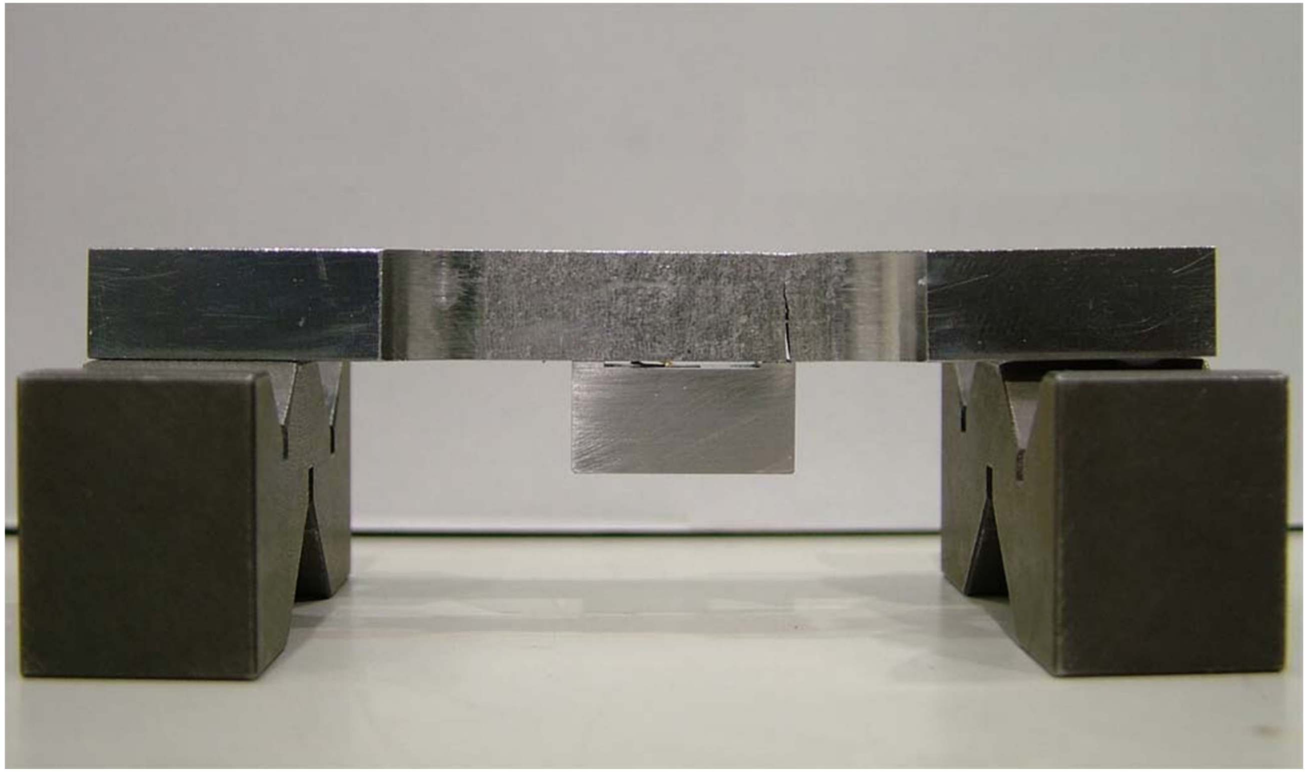
Interference fitting
(Press fit, Shrink fit)

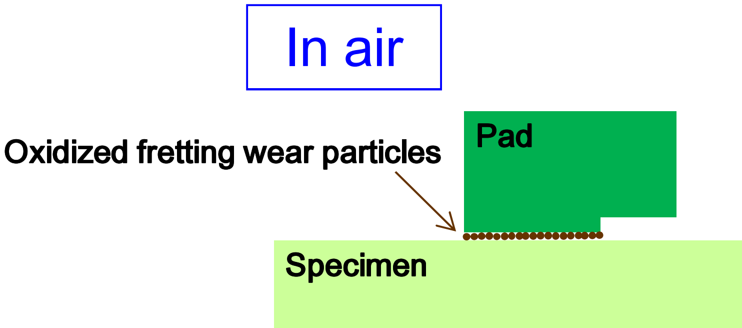


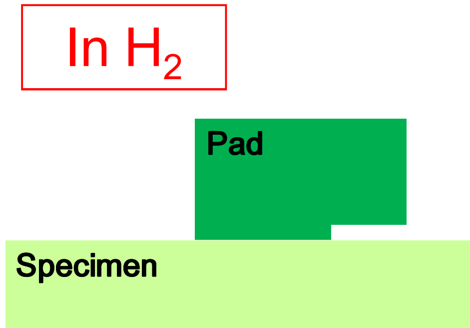


http://subal-m45.cocolog-nifty.com/blog/2008/09/post-151b.html

Adhesion during FF in H_2

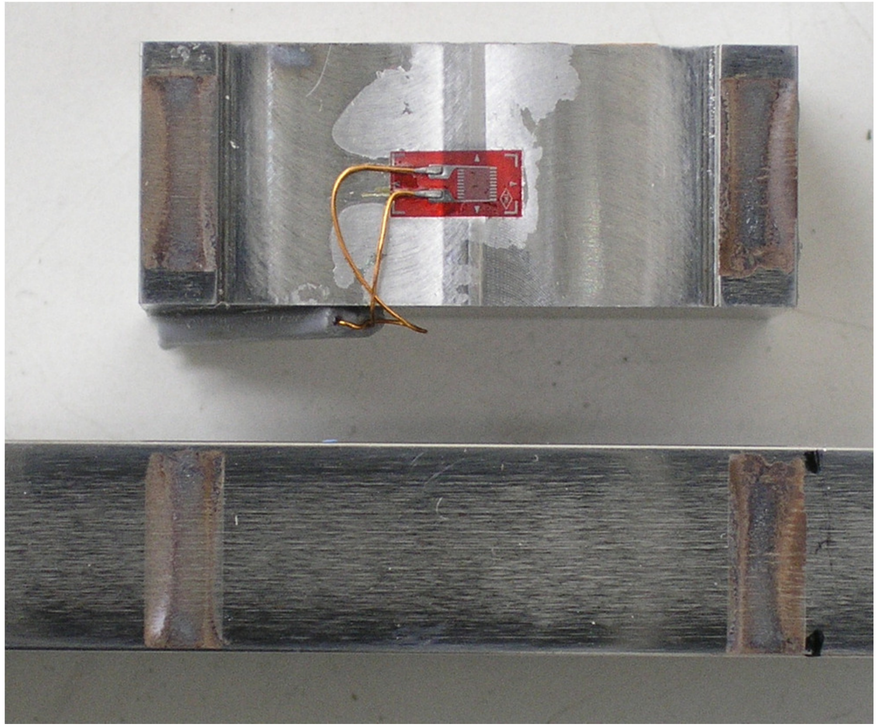




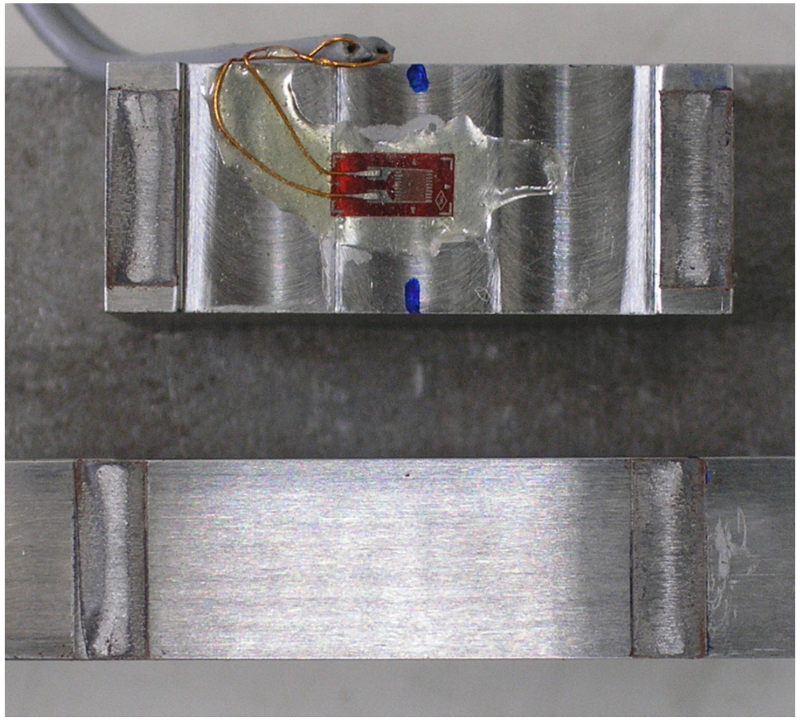


Fretted surface

In air



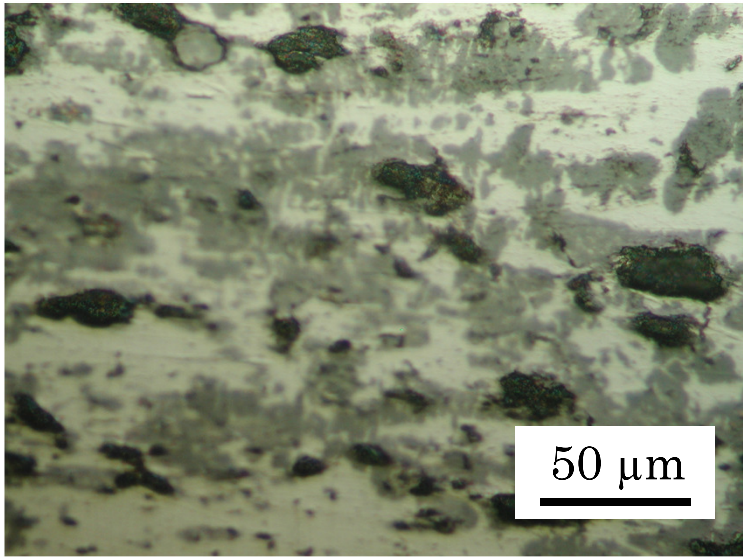
In H_2

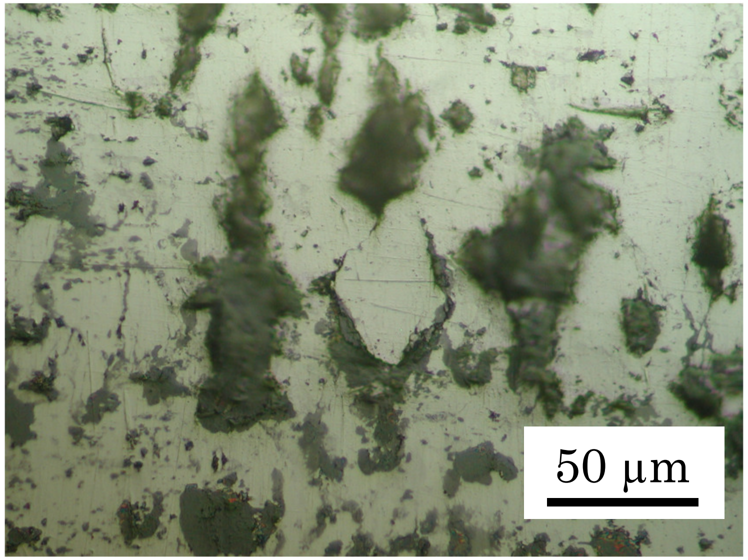


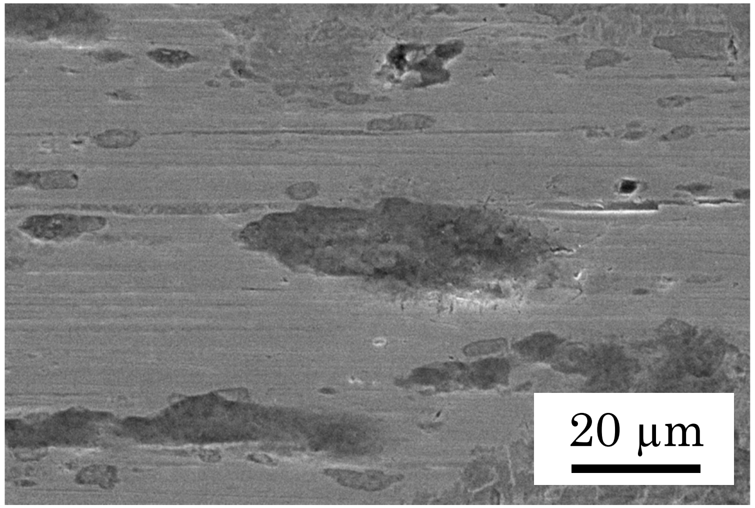
3mm

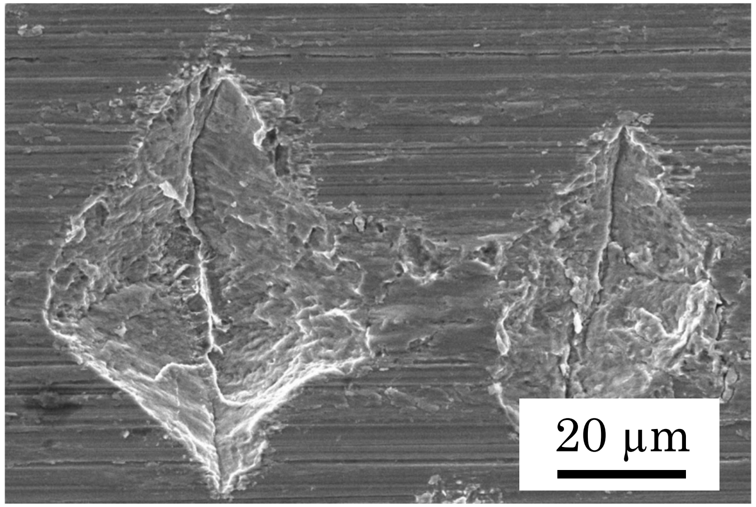
Fretting damage

In air | Fretting ⟷ | In H_2









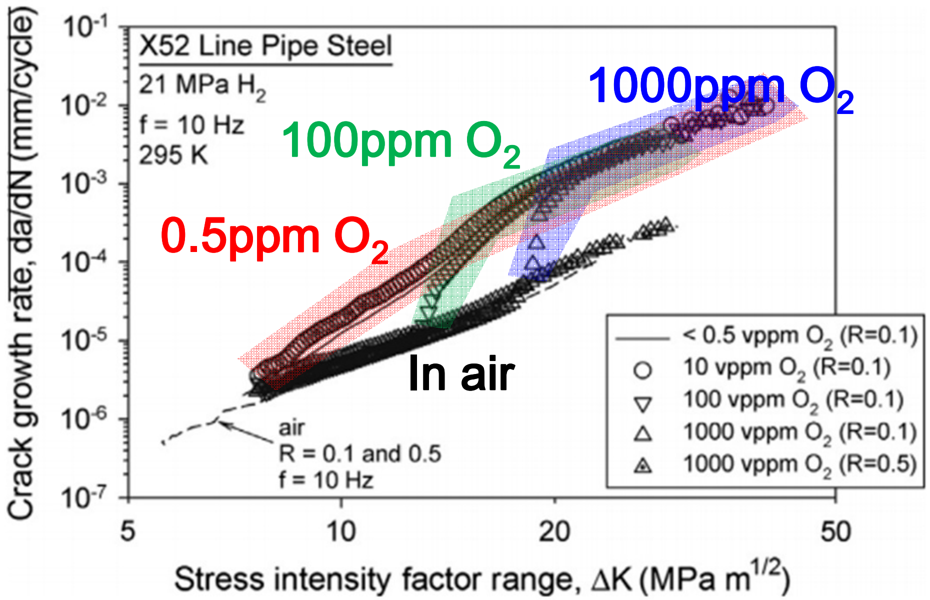
σ_a = 183 MPa, N_f = 2.96 × 10^6

σ_a = 188 MPa, N_f = 2.23 × 10^6

Effect of oxygen addition to H_2

Fatigue crack growth behavior

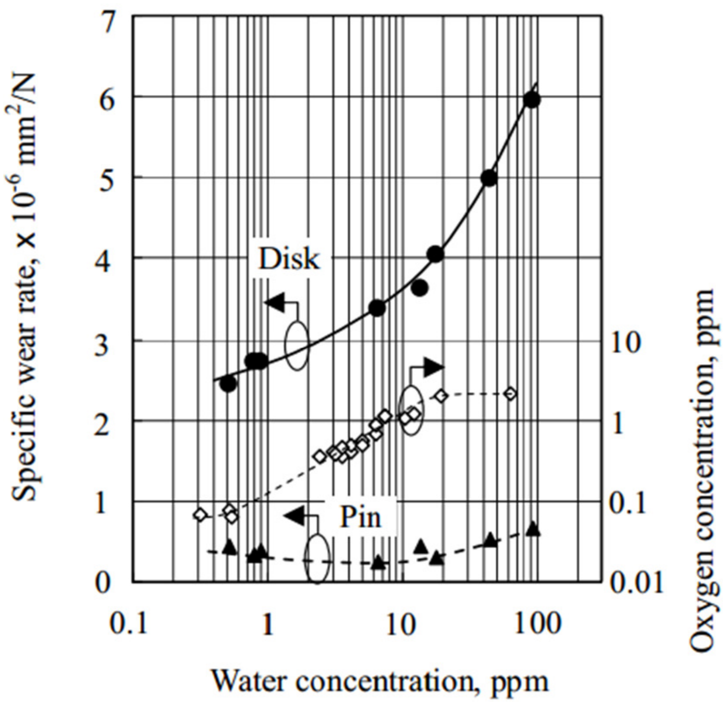
H_2 + 0.5 – 1000ppm O_2



Somerday BP, Sofronis P, Nibur KA, San Marchi C, Kirchheim R. Elucidation the variables affecting accelerated fatigue crack growth of steel in hydrogen gas with low oxygen concentrations. Acta Materialia 2013:61(16):6153-6170.

Wear behavior

H_2 + 0.01 - 10ppm O_2
H_2 + 0.5 – 100ppm H_2O



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Shift of crack initiation site by the addition of O_2