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International Institute for Carbon-Neutral Energy Research

Structural Materials Compatibility with Hydrogen

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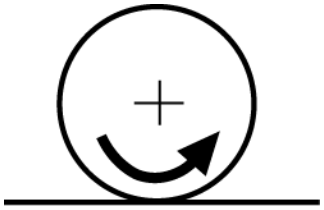
Background

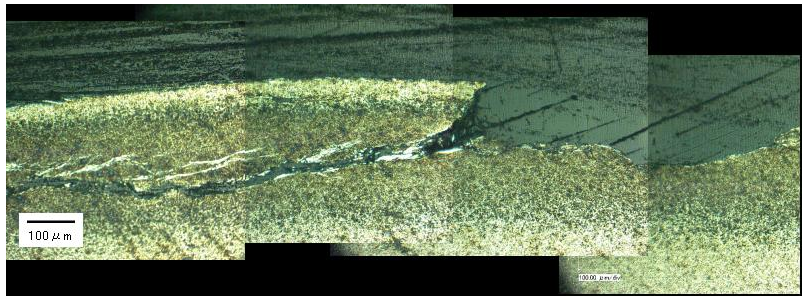
- ***H_2-induced material degradation leads to component failure, compromising safety and performance***

Rupture of steel H_2 cylinder
due to hydrogen embrittlement

Barthélémy, 1st ESSHS, 2006

Flaking failure in bearing due to hydrogen-accelerated rolling contact fatigue





Endo et al., 2003

Objectives/Relevance

- **Technology objective:** ***optimize cost, performance, and safety of H_2 containment and delivery systems***
- **Science objective:** ***establish fundamental knowledge to overcome barriers to new tools and technology***
- **Barriers/needs include:**
  - **Reliable and efficient methods for measuring effects of H_2 on fatigue, fracture, and wear properties of materials**
  - **Predictive models that include physics of H uptake, H-defect interactions, and material degradation**
  - **Next-generation materials having improved resistance to H_2-induced degradation at higher strength levels**
- ***Technical accomplishments map to these barriers/needs***

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Technical Approach

- **Approach to address barriers/needs**
  - **Conduct complex material property measurements in challenging environments, e.g., high-pressure H_2 gas**
  - **Define mechanisms of H-material interactions and material degradation using novel experimental/analytical methods**
  - **Apply modern material-processing methods to systematically study variables to improve H_2 compatibility**
- **7 groups in division represent 3 technical themes**
  - **Fatigue and fracture of materials**
  - **Friction and wear of materials**
  - **Materials processing**
- ***Natural alignment of groups in division***
  - **Example: 3 fatigue and fracture groups have shared research goals**
  - **Example: Productive, mutual dependence between fatigue and fracture groups and materials processing groups**

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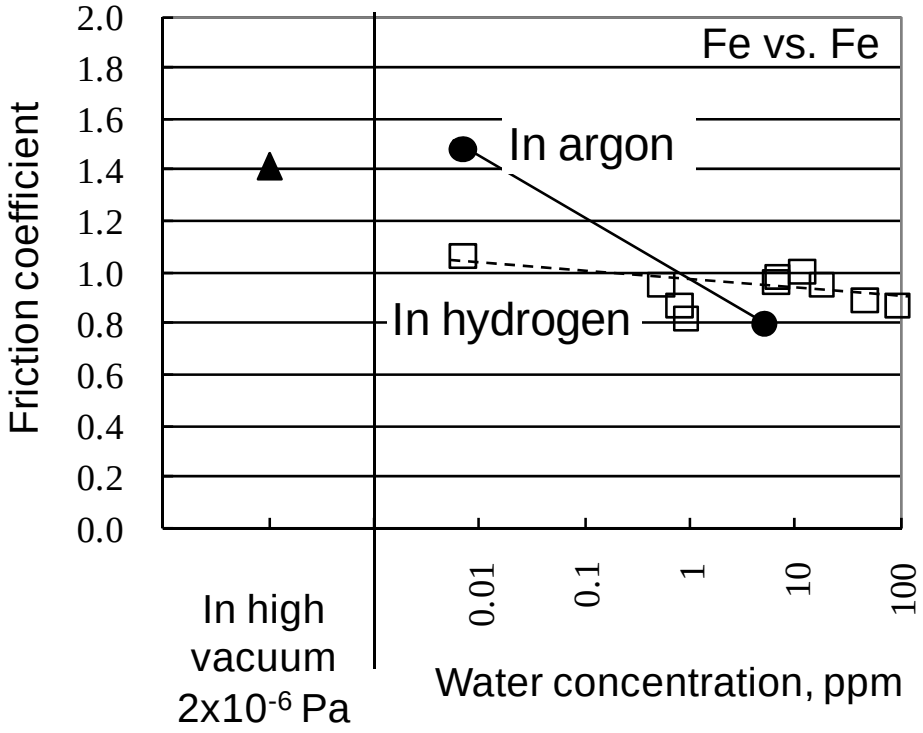
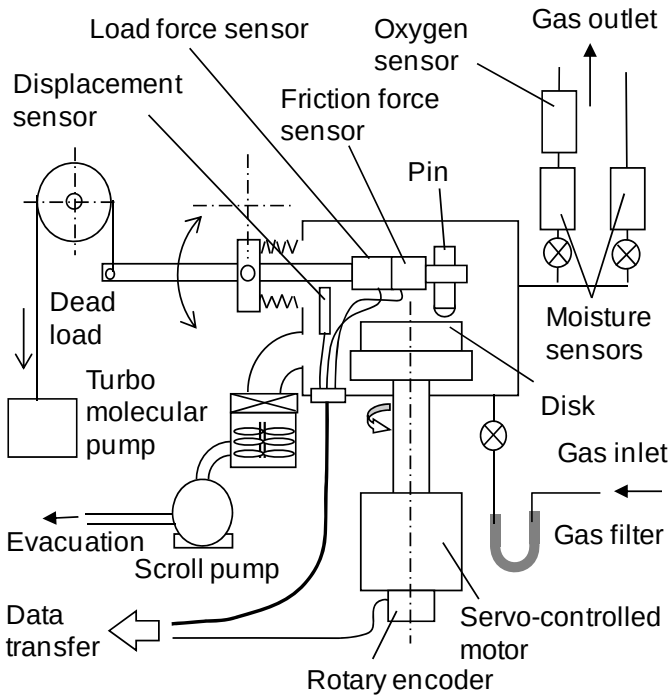
Friction coefficient of Fe vs. Fe measured with novel technique of controlling trace impurities

PI: Prof. J. Sugimura

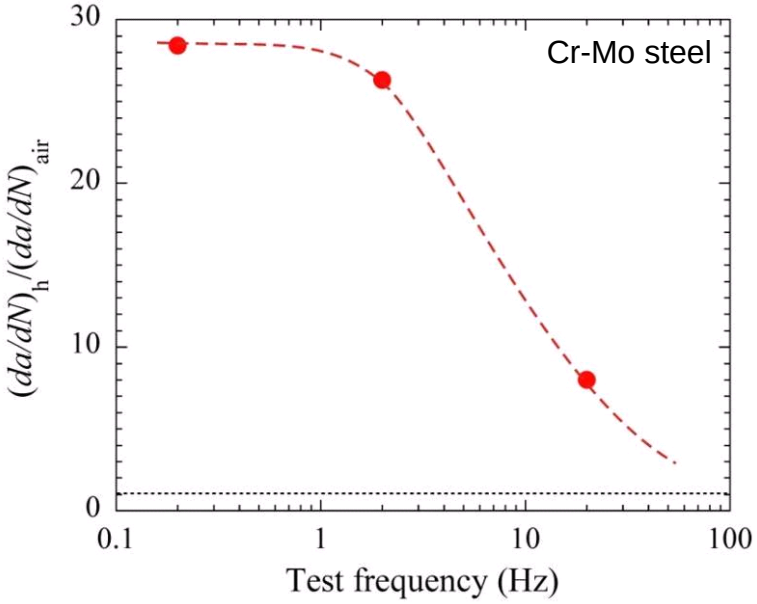


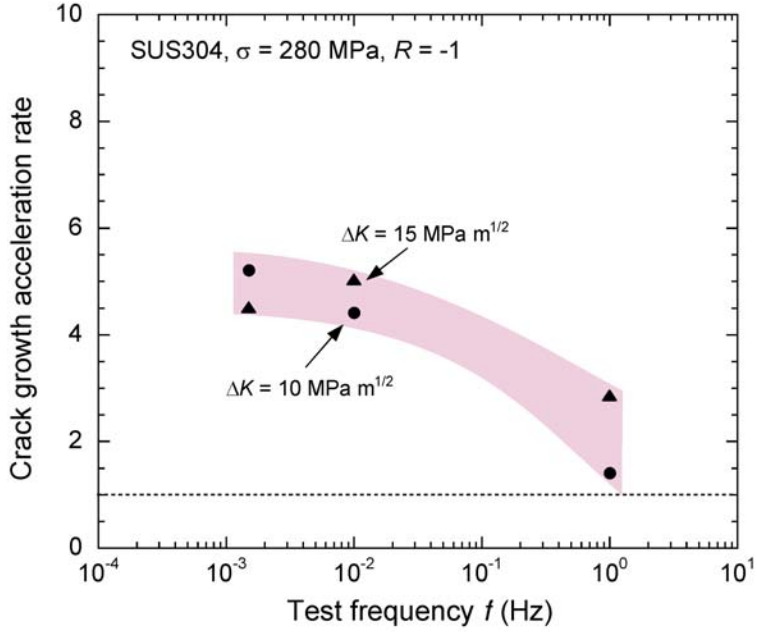


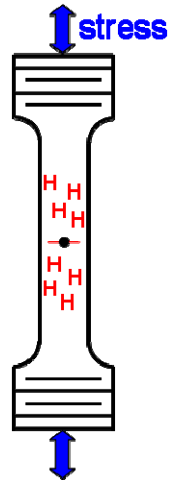
- **Represents first observation that chemisorbed H lubricates Fe surfaces in almost pure H_2 gas**
- **Results enhance basic understanding of tribochemical processes at metal-metal sliding contacts**

Effect of stress frequency on H_2-assisted fatigue crack growth depends on material structure

PI: Prof. Y. Murakami



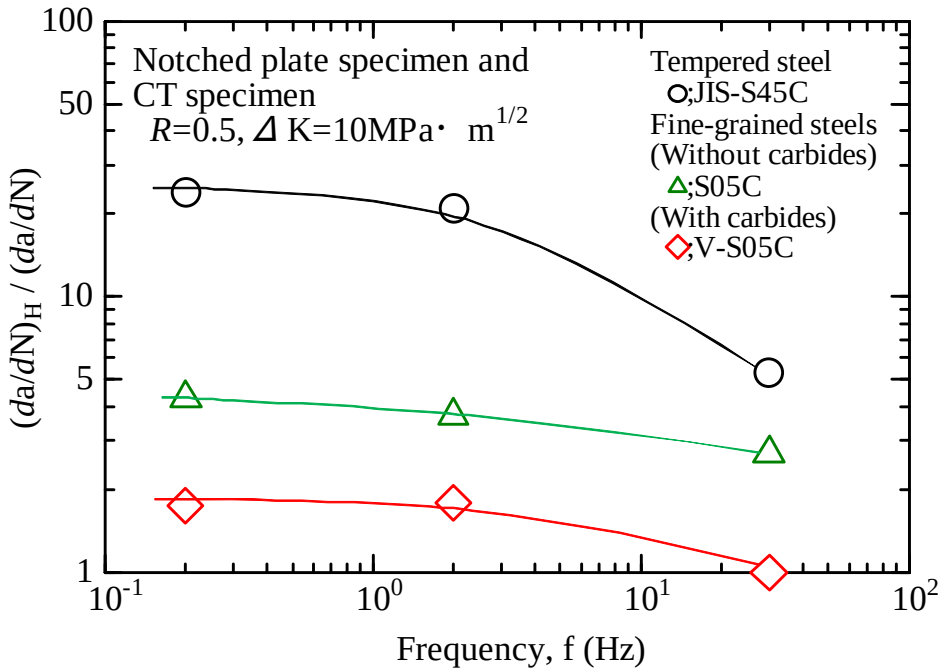


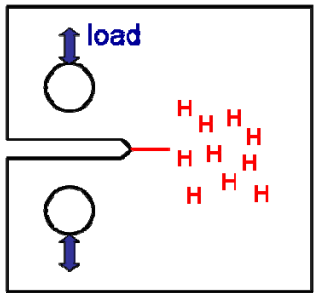


- **Optimizing stress frequency to balance data reliability and test efficiency significantly improves test methods**
- **Comprehensive crack growth rate vs. frequency data needed to develop predictive models**

Modifications to steel microstructure can mitigate H_2-assisted fatigue crack growth

PI: Prof. S. Matsuoka

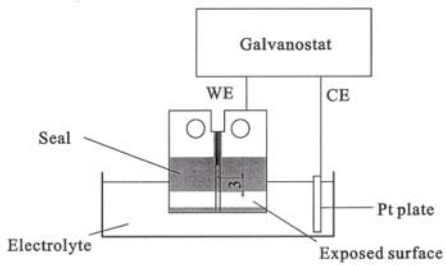


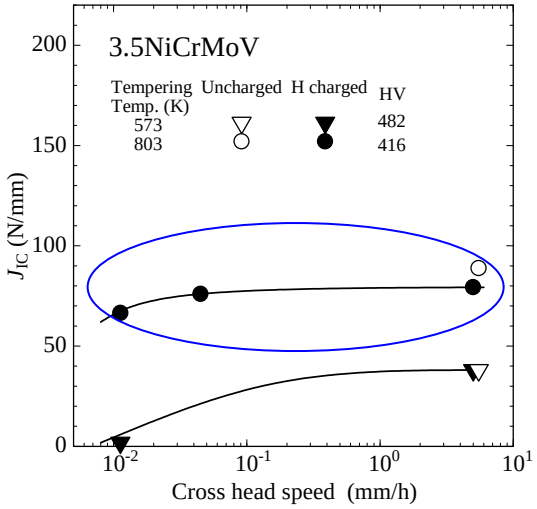


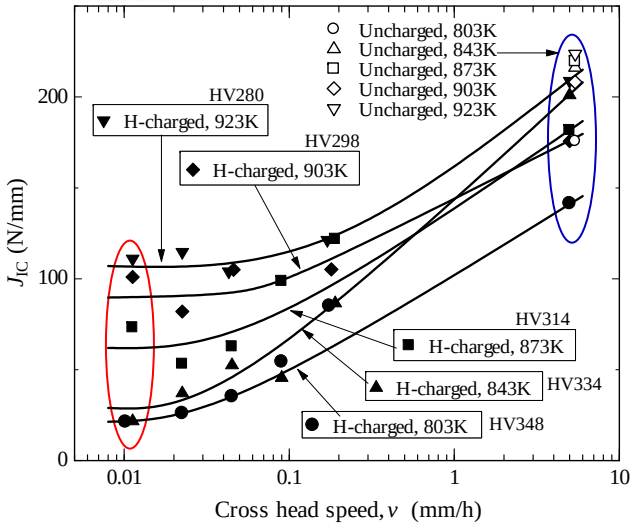
- **Results establish relationship between microstructure and properties**
- **Structure-property relationships enable understanding of H_2-induced material degradation mechanisms**

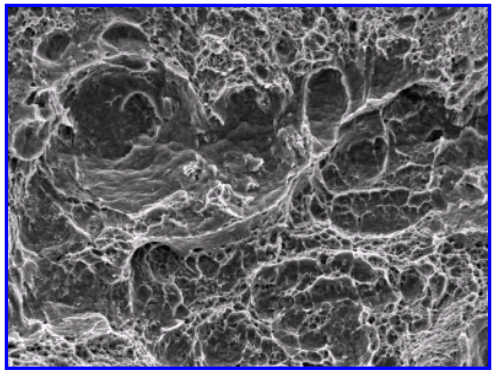
High-nickel steels appear more resistant to hydrogen embrittlement (HE)

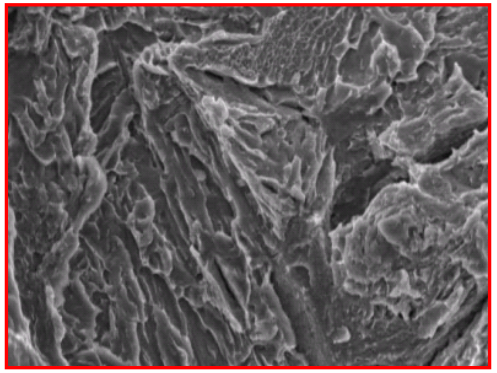
PI: Prof. Y. Kondo







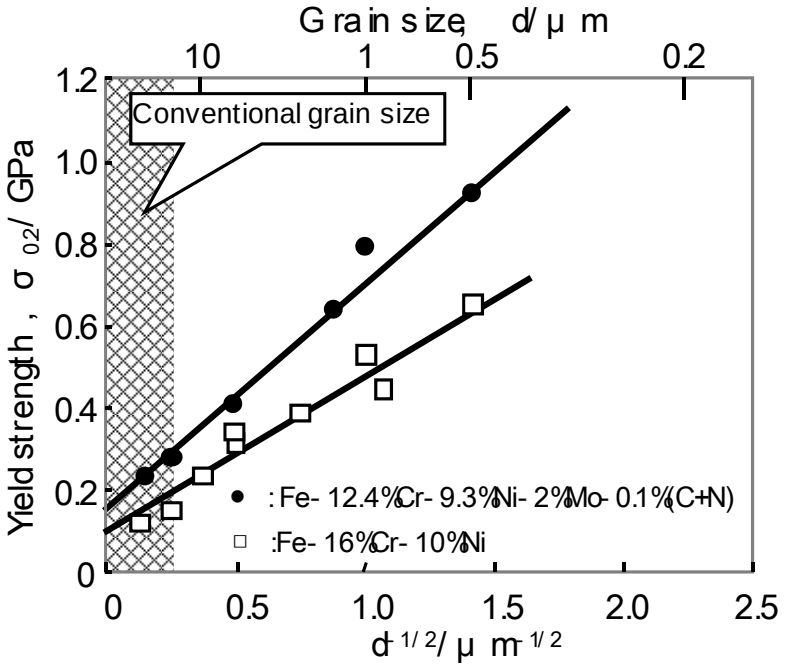


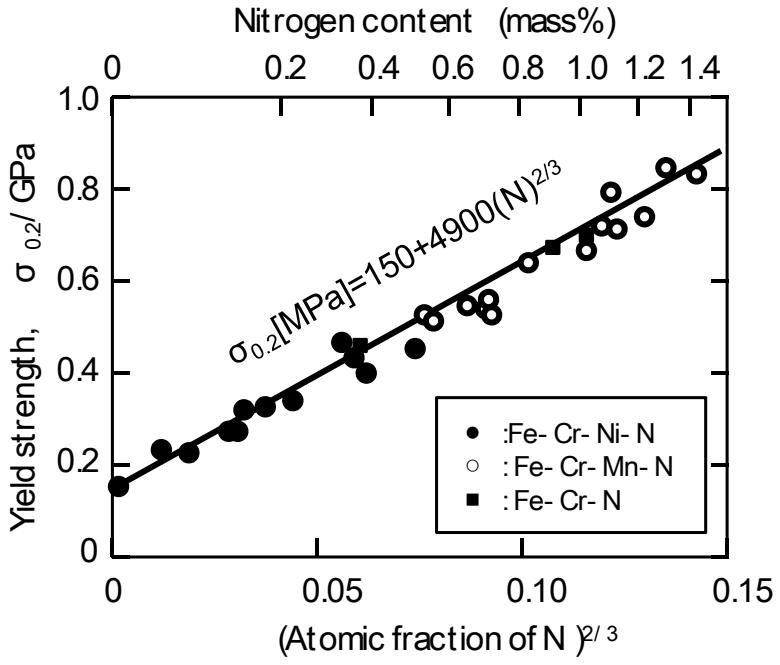


- **Results demonstrate pathway for exploring improved HE resistance in higher-strength steels**
- **Basic mechanism for improved HE resistance in high-nickel steels will be investigated**

Two novel stainless steels fabricated through grain refinement and nitrogen alloying

PI: Prof. S. Takaki





- **H_2-compatible, high-strength steels are important next-generation materials**
- **H_2 compatibility of steels evaluated in collaboration with fatigue and fracture groups in Division**

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Collaborations

- **Universities**
  - **University of Illinois (USA)**
- **Research Laboratories**
  - **Sandia National Laboratories (USA)**
  - **AIST (Japan)**
  - **National Institute of Materials Science (Japan)**
- **Industry**
  - **Mohawk Innovative Technology, Inc. (USA)**

Proposed Future Work

- Apply state-of-the-art focused ion beam-transmission electron microscopy (FIB-TEM) techniques to identify basic mechanisms of H-induced material degradation
- Measure fatigue and fracture properties of new high-strength stainless steels in high-pressure H_2 gas
- Characterize H_2-affected tribo-interfaces as a function of the component materials (metals, polymers, coatings) and environment (gases with trace impurities)
- Determine relationship between H_2-affected tribo-interfaces and crack nucleation in contact fatigue

Summary

- **Need: reliable and efficient methods for measuring effects of H_2 on fatigue, fracture, and wear properties**
  - **Optimizing stress frequency for measurements of H_2-assisted fatigue crack growth**
- **Need: predictive models that include physics of H uptake, H-defect interactions, and material degradation**
  - **Developing structure-property relationships to understand H_2-induced material degradation mechanisms**
  - **Enhancing basic understanding of tribochemical processes at metal-metal sliding contacts**
- **Need: next-generation materials with improved resistance to H_2-induced degradation at higher strength levels**
  - **Identifying candidate steels with higher strength for further investigation**

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Back-up Slides

Publications and Presentations

- Y. Murakami and S. Matsuoka, Effect of Hydrogen Content and Cyclic Frequency on Fatigue Crack Growth of a Cr-Mo steel and Austenitic Stainless Steels, Proc. Int. HYDROGENIUS & I2CNER Joint Symposium on Hydrogen-Materials Interaction, Int. Hydrogen Energy Development Forum 2011, Fukuoka, Japan
- Y. Murakami, T. Kanezaki and Y. Mine, Metall. Mater. Trans. A, 41, 2010, pp. 2548-2562
- T. Awane, Y. Fukushima, T. Matsuo, S. Matsuoka, Y. Murakami and S. Miwa, Highly sensitive detection of net hydrogen charged into austenitic stainless steel with secondary ion mass spectrometry, Analytical Chemistry, 83 (2011) pp. 2667-2676
- S. Matsuoka, H. Tanaka, N. Homma and Y. Murakami, Influence of hydrogen and frequency on fatigue crack growth behavior of Cr-Mo steel, Int. J. Fracture, 168 (2011) pp.101-112
- H. Ikemiya, M. Kubota and Y. Kondo, Effect of Loading Rate and Tempering Temperature on Fracture Toughness of Hydrogen-charged Low Alloy Steel SCM440H, *Trans JSME, Ser. A*, 77-775 (2011) pp. 483-494
- K. Fukuda, M. Hashimoto, J. Sugimura, Friction and Wear of Ferrous Materials in a Hydrogen Gas Environment, Tribology Online, Vol.6, No.2, pp.142-147
- H. Tanimoto, H. Tanaka and J. Sugimura, Observation of Hydrogen Permeation into Fresh Bearing Steel Surface by Thermal Desorption Spectroscopy, submitted, 2011
- M. Kubota, K. Kuwada, Y. Tanaka, Y. Kondo, Mechanism of reduction of fretting fatigue limit caused by hydrogen gas in SUS304 austenitic stainless steel, Tribology International, in press, 2011
- K. Mizobe, Y. Shiraishi, M. Kubota, Y. Kondo, Effect of Hydrogen on Fretting Fatigue Strength of SUS304 and SUS316L Austenitic Stainless steels, Proceedings of the JSME/ASME 2011 International Conference on Materials and Processing (ICM&P2011), June 13-17, 2011, Corvallis, Oregon, USA
- K. Edalati, A. Yamamoto, Z. Horita and T. Ishihara, High-pressure torsion of pure magnesium: Evolution of mechanical properties, microstructures and hydrogen storage capacity with equivalent strain, Scripta Mater., 64, 2011, pp. 880-883

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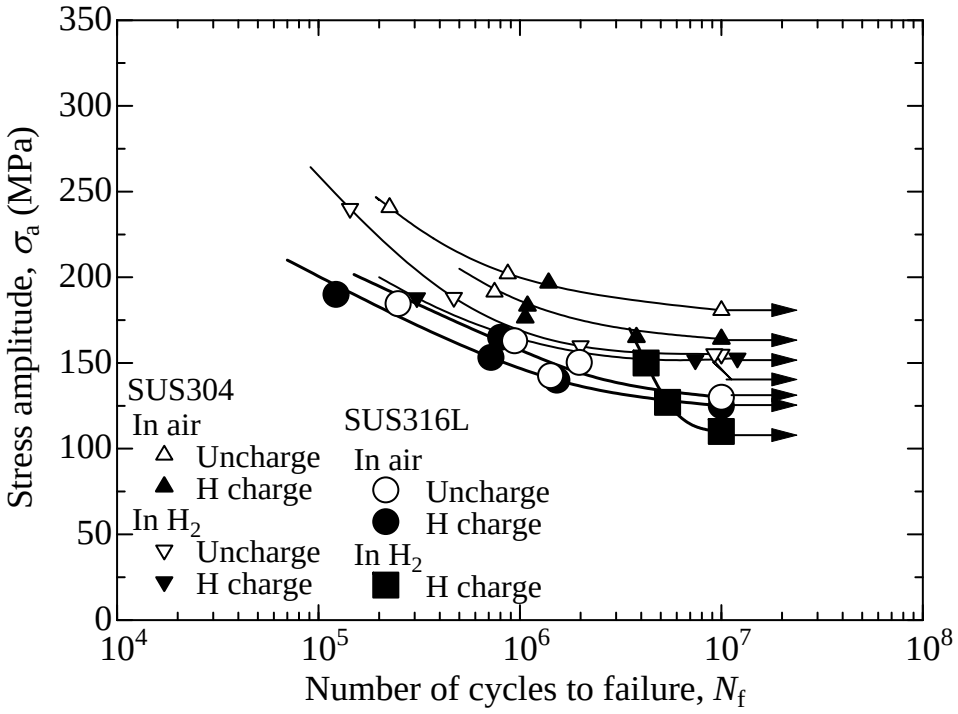
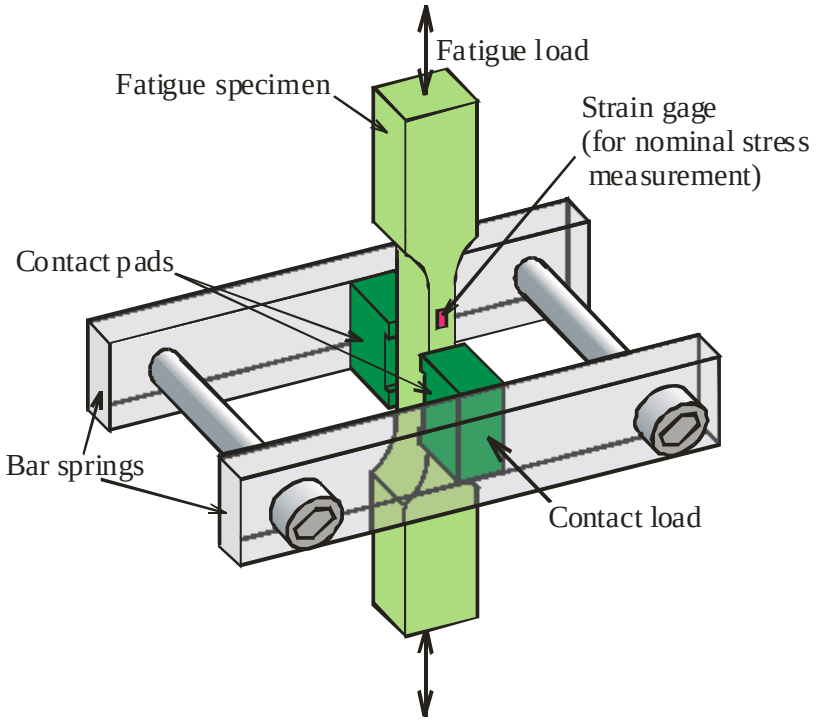
Other technical slides

Comprehensive evaluation of H_2 effects on fretting fatigue strength completed

PI: Prof. M. Kubota





- **Results establish necessary structure-property relationships for fretting fatigue**
- **Structure-property relationships enable understanding of H_2-induced material degradation mechanisms**

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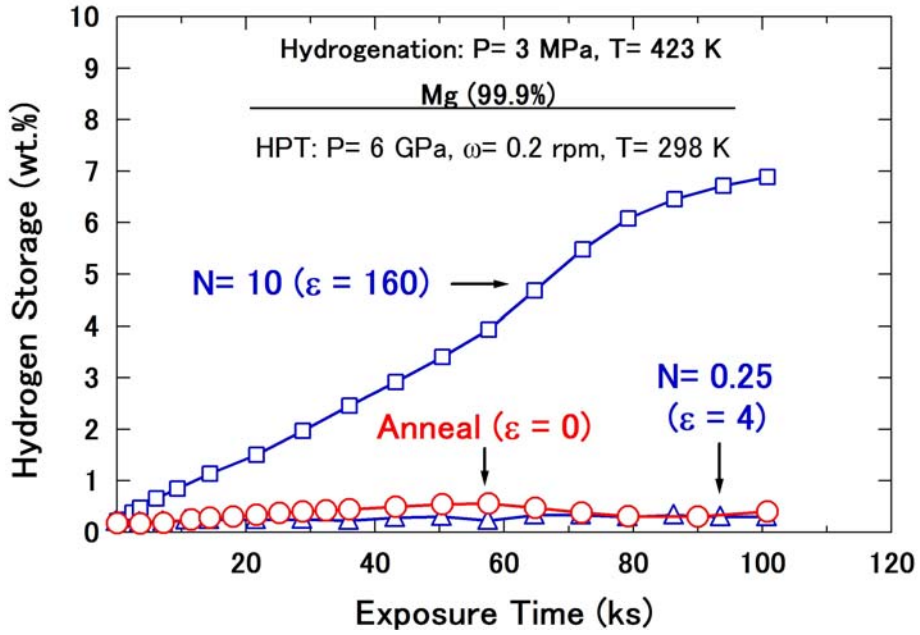
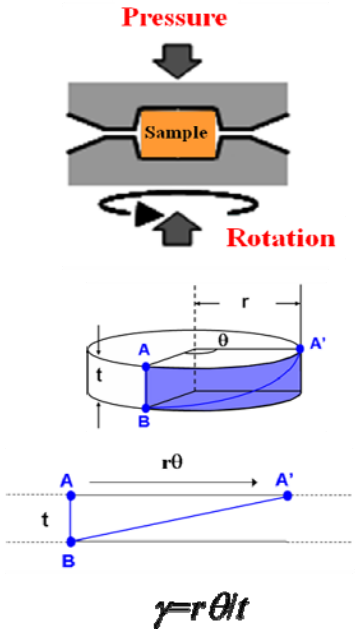
High-pressure torsion (HPT) processing enables basic H-defect interaction studies

PI: Prof. Z. Horita





- **Grain size refinement in Mg enhances total hydrogen concentration**
- **Controlled processing essential for studying material variables that govern degradation mechanisms**