III.10 Investigation of H_2 Diaphragm Compressors to Enable Low-Cost Long-Life Operation

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Project Start Date: June 1, 2013
Project End Date: December 31, 2013

Overall Objectives

Reduce compressor operation and maintenance cost by reducing instances of diaphragm failure and the resulting need for repair of hydrogen gas compressors

Fiscal Year (FY) 2013 Objectives

- Identify the causes for the reduced lifetime of the diaphragm compressors operated under start-stop mode
- Develop material and compressor design solutions to enhance the lifetime of diaphragm compressors

Technical Barriers

This project addresses the barrier "B" from the Hydrogen Delivery section from the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(B) Reliability and Costs of Gaseous Hydrogen Compression

Technical Targets

This project conducted research to decrease compressor operations and maintenance costs by improving the reliability of hydrogen compressors. Understanding gained from this work will be applied to future compressors to enable them to meet DOE 2015 compressor targets:

- 2.5% of installed capital cost for maintenance
- Improved reliability and life

Accomplishments

This project was developed in conjunction with PDC Machines, Inc., a commercial supplier of diaphragm hydrogen compressors. The project accomplishments are:

- Contamination/debris in the H_2 gas and improper priming procedures when restarting a compressor after stopping have been identified as two important factors that adversely affect the life of the diaphragm.
- A finite element model (FEM) of the diaphragm was developed to predict the location on the diaphragm where the maximum stress and maximum contact sliding occur relative to the compressor process head. Both the maximum stress and maximum contact sliding occur where failures are typically observed in PDC's compressor diaphragms.
- A second FEM was developed to estimate the contact and residual stresses that could occur if debris is trapped against the head profile during the compression stroke. The results showed that the operating pressure is high enough to cause local plastic deformation around trapped hard particles leaving residual stresses that could reduce the fatigue life of the diaphragm.
- The location and orientation of the primary crack in a failed diaphragm, taken out of service, indicated the importance of radial stresses in the diaphragm failure. Significant plastic deformation could be seen in the primary crack region while numerous stringers, oriented in the sheet rolling direction, were also observed in the sheet cross section.

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INTRODUCTION

The goal of this project is to reduce the instances of diaphragm failures and the resulting need for repair of hydrogen gas compressors. Achieving this goal will help enable economical operation of hydrogen vending stations in support of DOE's goal of developing a hydrogen distribution network. The short life of compressor diaphragms subjected to intermittent operation is a key hurdle in developing an economical hydrogen distribution network. This hurdle exists because the repair costs and the down time associated with repeated compressor breakdown may substantially increase the costs for fueling stations for hydrogen fuel cell vehicles. Consequently, there is a need to enhance the life of hydrogen compressors to successfully establish a wide-spread hydrogen distribution network via the existing gas stations and new hydrogen stations. For this project, PNNL has partnered with PDC Machines, Inc., a leader in hydrogen compressor technology, to develop materials and engineering solutions to the problem of repeated breakdown of hydrogen compressors. The team investigated the diaphragm failures through finite element modeling of the diaphragm, and through materials characterization of commercially manufactured diaphragms.

APPROACH

Material characterization and engineering stress analysis were performed to study why diaphragm compressors require more frequent maintenance when they are operated intermittently than when they are operated continuously. PNNL worked with PDC Machines, Inc. to analyze the design and operating performance of one of PDC's commercially available diaphragm compressors. FEMs (using ANSYS software) were developed to understand the diaphragm deformation and stresses as it bears against the compressor cavity during the compression stroke. A second model was developed to predict the contact stresses and plastic damage that may occur if contaminant particles were trapped and compressed between the diaphragm and the compressor head. A scoping study was also initiated to develop a combined Eulerian-Lagrangian model of the dynamic oil flow and local pressure distribution and deformation of the diaphragm.

The materials characterization effort comprised analysis of commercial diaphragm materials provided by PDC Machines. A failed diaphragm taken out of service was examined using optical and electron microscopy. The location and orientation of the crack was examined and related to the stress distribution predicted by finite element analysis. The microstructure of the diaphragm materials was analyzed using optical microscopy and the electron backscatter diffraction technique. Finally, the crack and adjoining microscale features were analyzed using scanning electron microscopy (SEM).

RESULTS

Figure 1 shows a used PDC diaphragm that was removed from service due to cracking. The diaphragm shows a ring of black deposit, possibly generated from impurities in the H_2 gas, which is suspected to be one cause of reduced diaphragm life. The finite element analysis (Figure 2) showed that both the maximum sliding displacement and the maximum radial stresses occur in the same location where diaphragm cracking is typically observed. This is close to the ring of black deposit in Figure 1, which could potentially be a site for fretting damage and subsequent failure, especially in the presence of any debris. Finite element analysis showed that the operating pressure is high enough that contact stresses from debris compressed against the diaphragm could cause plastic surface damage with accompanied high residual stresses that could lead to surface wear and reduced fatigue life.

FIGURE 1. Picture of a PDC diaphragm taken out of service, showing the ring of black deposit suspected to be a cause of reduced diaphragm life. The location of the crack, where the diaphragm leaked, is circled with a black marker.

Examination of the failed diaphragm showed that the primary crack was approximately perpendicular to the radial direction, suggesting that mode I fracture under high radial stresses was the likely cause of diaphragm failure. Multiple microcracks were also observed adjacent to the primary crack and were found to be oriented perpendicular to the sheet rolling direction. At places, the surface of the diaphragm appeared to stretch across the primary crack, suggesting significant plastic deformation associated with the failure (e.g. see Figure 3). Microstructural analysis in the sheet through-thickness direction showed numerous oriented stringers (see Figure 4) that were formed during the sheet's prior thermo-mechanical treatment. Such 2nd phase particles can have an adverse effect on the diaphragm's fatigue life.

CONCLUSIONS AND FUTURE DIRECTIONS

This project has enabled PNNL to begin developing a fundamental understanding of design, materials and operational issues that affect the diaphragm life. The FEM approach was successful, to a first approximation, in predicting potential failure locations that matched closely with the observed failure location. The FEM results also emphasize the importance of diaphragm sizing, the inner contour of the compressor head and debris on the stress distribution in the diaphragm and the potential for failure. Microstructural analysis of the diaphragm provided insights into how failure was affected by the stress distribution and

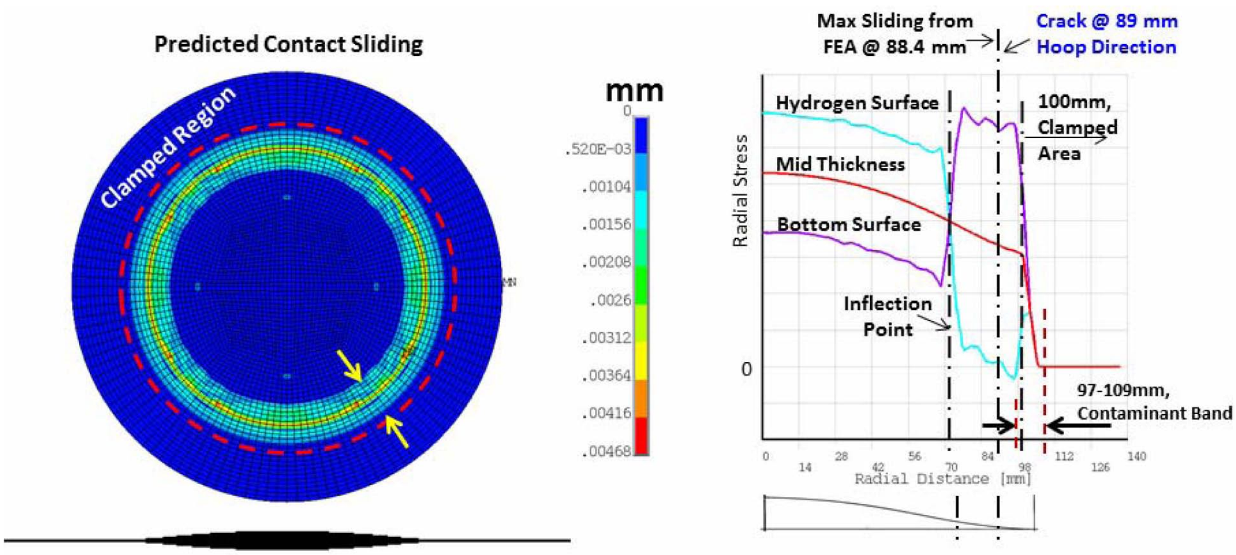

FIGURE 2. Left: The yellow contour band indicates the radial location of maximum sliding, which coincides with the ring of black deposit in Figure 1. Right: Maximum stress also coincides with maximum sliding and location of fracture in the diaphragm (stress magnitudes are PDC proprietary).

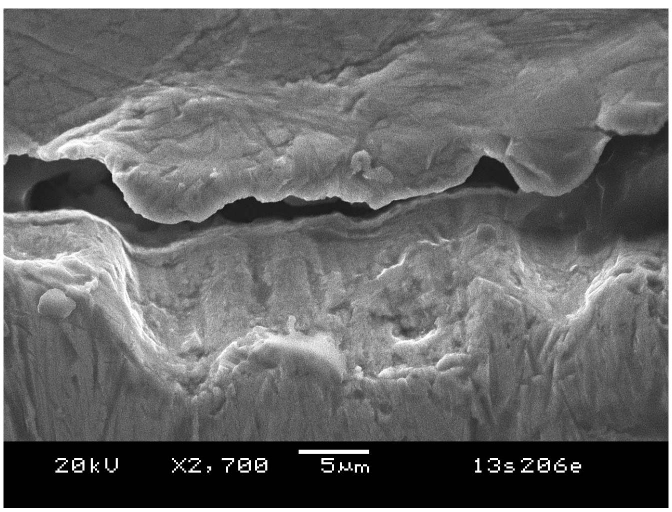

FIGURE 3. A SEM image of a portion of the crack (from diaphragm shown in Figure 1) showing plastic deformation in the diaphragm associated with the crack.

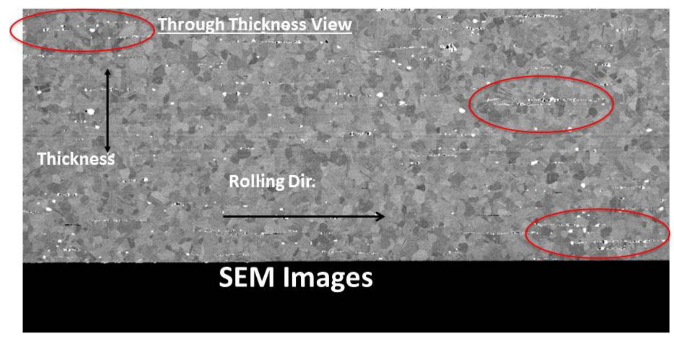

FIGURE 4. A through thickness back-scatter electron image of a diaphragm showing numerous stringer particles (bright features enclosed within the ellipses) that are aligned along the sheet rolling direction. (Grain size is PDC proprietary.)

potentially deleterious features in the microstructure and surface texture.

We anticipate that this partnership and information and knowledge exchange between the industry and a national laboratory will be critical in helping DOE achieve its targets for improving compressor reliability, increase diaphragm life and reduced maintenance costs. The following are three potential areas for further research to enable long life for H_2 compressors:

- Understanding the role of diaphragm microstructure in controlling its operational life.
- Design tools for evaluating interactions between compressor design, fluid flow, and diaphragm response.
- The effect of impurities and debris on fatigue life of the diaphragm.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. Aashish Rohatgi, Ken Johnson, Naveen Karri, Ayoub Soulami, Jamie Holladay, Kareem Afzal, *"Investigation of H2 Diaphragm Compressors to Enable Low-Cost Long-Life Operation."* Presented at the Hydrogen Delivery Tech Team meeting, September 12, 2013, Sandia National Laboratories.

2. KI Johnson, A Rohatgi, and NK Karri. *"A Modeling and Microstructural Investigation of H2 Diaphragm Compressors to Enable Low-Cost, Long-Life Operation."* PNNL-SA-103662. Poster presented at the ASME 12th Fuel Cell Science, Engineering and Technology Conference, June 30 – July 3, 2014. Boston, MA.