A Study of the Sealing Performance of a New High-Pressure Cone Valve for Deep-Sea Gas-Tight Water Samplers

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The cone valve plays an important role in high-pressure sealing applications. In this paper, a new high-pressure cone valve, based on the titanium alloy poppet-to-polyetheretherketone seat sealing structure, is proposed for deep-sea gas-tight water samplers. In order to study the sealing performance of the new valve, both the conforming poppet-seat contact model and the nonconforming poppet-seat contact model were evaluated. Finite element analysis based on the two models was performed and validated by experiments. The results indicate that the nonconforming poppet-seat contact model has a better sealing performance than the conforming poppet-seat contact model. The new cone valve also was applied in a gas-tight hydrothermal fluid sampler and successfully tested in a sea trial during the KNOX18RR cruise from 9 July to 12 August 2008. [DOI: 10.1115/1.4001204]

Keywords: *high pressure, cone valve, finite element analysis, deep sea*

1 Introduction

During the process of sampling deep-sea hydrothermal fluid and seawater, maintaining in situ pressure is usually an important requirement for the samplers when samples are used for the analysis of quantitative gas components and the investigation of barophilic microorganisms [1–3]. In fact, effective sealing is the key factor for maintaining the pressure. The deep-sea gas-tight sampler usually employs a sampling valve to collect the fluid sample. For the hydrothermal fluid sampler, the sampling valve must have bidirectional sealing capability to prevent incursion of seawater during descent and loss of sample during ascent. Although the commercial valves, such as needle valves, are available for deep-sea equipment, they are usually difficult to actuate. For example, the hydrothermal fluid sampler needs an especially designed motor-actuating mechanism to control the sampling valve [1]. In previous work, a novel sampling valve with a pressure-balanced polyetheretherketone (PEEK) poppet, which can be actuated by the ram on a submersible's manipulator, was designed and applied to the hydrothermal fluid gas-tight sampler [4]. The motivation to use PEEK material is due to its high strength, thermal tolerance, (260°C for long-term use) and corrosion resistance [5]. However, because the PEEK poppet is affected by axial tensile force under inner pressure, it has the potential to rupture when the tension exceeds the tensile strength of the PEEK material [6].

In order to address these issues, a new high-pressure cone valve was designed for the gas-tight sampler. The new cone valve utilizes a titanium alloy valve poppet and a PEEK seat to construct the sealing structure. Because the titanium alloy has a much higher tensile strength than the PEEK, it minimizes the possibility for rupturing the valve poppet under high pressure. Moreover, the facts that the conforming poppet-seat contact structure in which the valve poppet and seat have the same cone angle and the nonconforming poppet-seat contact structure in which the valve poppet has a smaller cone angle than the seat were considerations for the cone valve design. Finite element analysis (FEA) and experiments were performed to investigate the sealing performances of the two kinds of sealing structures.

Contributed by the Pressure Vessel and Piping Division of ASME for publication in the Journal of Pressure Vessel Technology. Manuscript received June 20, 2009; final manuscript received February 1, 2010; published online August 5, 2010. Assoc. Editor: L. Ike Ezekoye.

2 Structure Design and Construction

As Fig. 1 shows, the new high-pressure cone valve mostly employs two sliding O-ring seals and a cone seal comprising of a valve poppet and seat. Unlike the use of a single-valve poppet in the previous design, described by Chen et al. [4], the new valve is designed with a valve poppet and a sliding spool, resulting in a better axial alignment of the poppet and seat. Because the two sliding O-ring seals and the valve seat have the same diameter (Fig. 2), the valve poppet is pressure balanced when the inlet port is subjected to high pressure. Therefore, the sealing force does not vary with operating fluid pressure. Conversely, when the outlet port is subjected to high pressure, the valve poppet is compressed more and more tightly against the seat with the increase in fluid pressure, resulting in a better sealing performance than the inlet port. This special aspect of the new valve is different from the previous sampling valve, the valve poppet of which is always pressure balanced [4]. In the common cone valve, the valve poppet and seat usually have the same cone angle, leading to a conforming poppet-seat contact [7]. In order to achieve a more reliable sealing performance, the nonconforming poppet-seat contact, which is accomplished by choosing a cone angle of the poppet smaller than that of the seat, was also considered in the design of the new high-pressure cone valve. Another feature of the valve is its capability for high-temperature tolerance and corrosion resistance, implemented by selecting special material for manufacturing the valve. Besides the PEEK seat, other valve parts in contact with a fluid sample, including the valve body, valve poppet, sliding spool, valve sleeves, and support ring, are all made of a 6-aluminum–4-vanadium alloy of titanium (commonly referred to as Ti–6Al–4V). A titanium alloy was chosen for the valve because

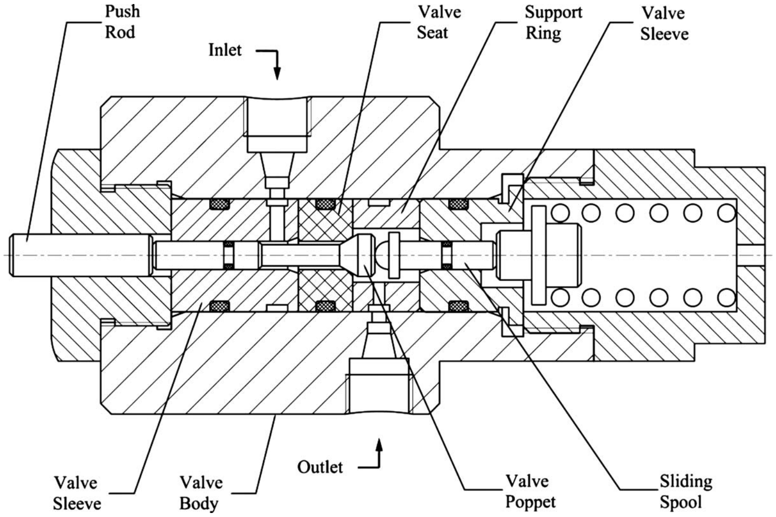

Fig. 1 Schematic illustration of the high-pressure cone valve

of its special resistance to corrosion, its high strength, and its low density. All the O-rings of the valve are made of perfluoroelastomer.

3 Finite Element Modeling

A two-dimensional (2D) axisymmetrical finite element (FE) model of poppet-seat interface was developed using the ANSYS software. The geometry of the FE model is shown in Fig. 3. A conforming poppet-seat contact and a nonconforming poppet-seat contact have been taken into account in the FE model. The semicone angle of the valve poppet (designated α_1 in Fig. 3) is kept constant at 30 deg, whereas the semicone angle of the seat (designated α_2) is 30 deg for the conforming contact model and 32.5 deg for the nonconforming contact model. The 2D structural solid-element PLANE 183 is used to model the valve seat. As the valve poppet is made of titanium alloy, which is much stiffer than PEEK (the material for the valve seat), the valve poppet can be assumed to be nondeformable during compression. Therefore, it is considered to be a rigid body in the FE model. The interface between the poppet and seat is modeled with surface-to-surface contact elements, CONTA172 (on the seat side) and TARGE169 (on the poppet side). In the FEA model, the displacement loads to the valve poppet were applied in steps.

Nonlinear material properties were considered during FEA. The seat material was assumed to be elastic-plastic with multilinear isotropic (MISO) hardening. The material model is presented in Fig. 4. In considering the large strain effect, the stress-strain relationship in Fig. 4 is described in terms of true stress and true strain, which were converted from the engineering stress and engineering strain obtained from Victrex PEEK properties [5]. The elastic modulus and Poisson's ratio of PEEK were 3500 MPa and 0.4, respectively.

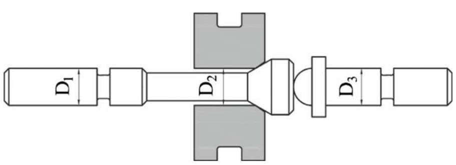

Fig. 2 Valve poppet and seat; $D_1=D_2=D_3$

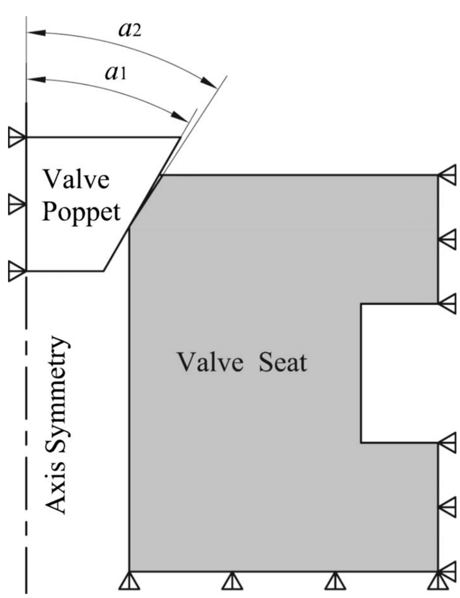

Fig. 3 FE model

4 FEA Results

As a description of the sealing process [8], the poppet displacement versus force responses during compression were used and are illustrated in Fig. 5. For the conforming poppet-seat contact

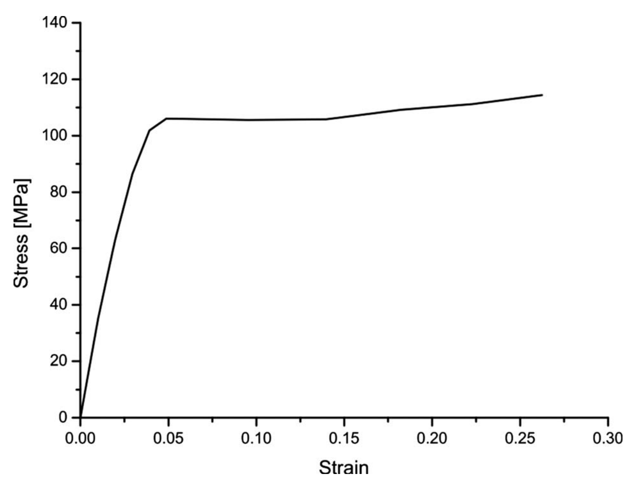

Fig. 4 PEEK material model

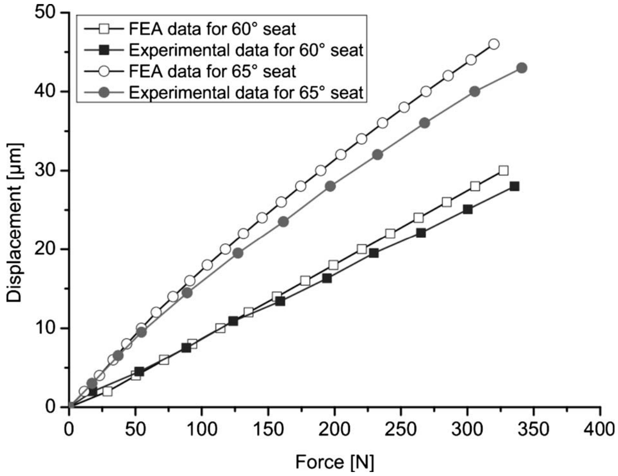

Fig. 5 Displacement versus force curves for the valve poppet-seat compression, resulting from FEA and experiments. The cone angle of the poppet is 60 deg, and the cone angles of two seats are 60 deg and 65 deg.

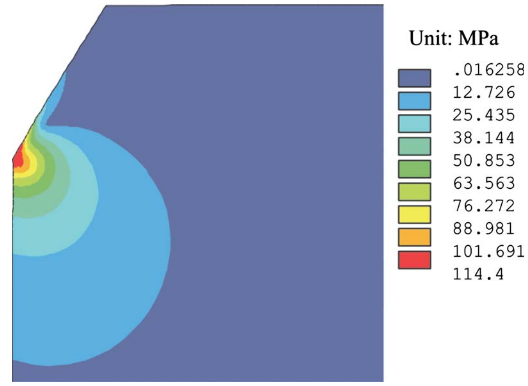

Fig. 7 Von Mises equivalent stress distribution of valve seat with cone angle of 65 deg. Compressive force is 320 N.

(with the valve seat of the 60 deg cone angle), the displacement is linear with the compressive force, indicating that deformation of the valve seat is elastic. The nonlinearity of displacement versus force response is observed when the poppet-seat contact is nonconforming (with a valve seat of 65 deg cone angle), which indicates that the valve seat underwent an elastic-plastic deformation stage. This can be identified by von Mises equivalent stress distributions for valve seats with cone angles of 60 deg and 65 deg when the compressive forces are 327 N and 320 N, respectively. As shown in Figs. 6 and 7, the maximal von Mises equivalent stress for a valve seat of a 60 deg cone angle is 78 MPa, which is less than the yield point of PEEK (95 MPa). The maximal von Mises equivalent stress for a valve seat of a 65 deg cone angle is 114 MPa, which indicates the appearance of plastic deformation. The comparison of displacement versus force curves, shown in Fig. 5, also can lead to the conclusion that the nonconforming poppet-seat contact structure has a relatively larger deformability, thus enabling a better mating surface between valve poppet and seat.

In addition to needing a mating surface between valve poppet and seat, effective sealing also requires adequate contact pressure on the interface [9–12]. The contact pressure distributions along the contact faces for conforming poppet-seat contact model and the nonconforming poppet-seat contact model are shown in Fig. 8. The contact pressure is relatively more homogeneous on a valve seat with a cone angle of 60 deg, and its average value is 36 MPa. However, the contact pressure on a valve seat with a cone angle of 65 deg decreases dramatically along the contact face, with an initial maximum value of 158 MPa. Moreover, its average value is 91 MPa, which is much higher than that on a valve seat with a cone angle of 60 deg. Generally, high contact pressure is responsible for reliable nonleakage sealing. Therefore, this can lead to the conclusion that the nonconforming poppet-seat contact model will achieve a better sealing performance under high pressure than the conforming poppet-seat contact model.

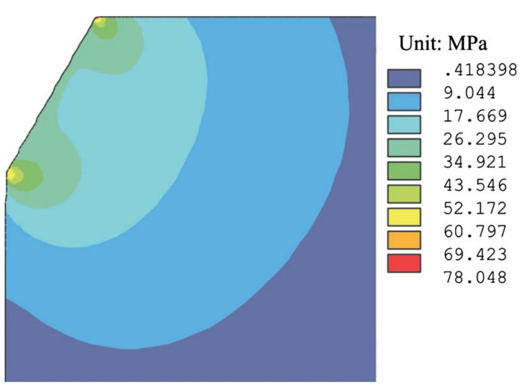

Fig. 6 Von Mises equivalent stress distribution of valve seat with cone angle of 60 deg. Compressive force is 327 N.

5 Experiments

In order to validate the FEA, the poppet-seat compression tests and sealing experiments of a valve under high pressure were performed. The experimental system is schematically shown in Fig. 9. During the poppet-seat compression tests, a dial indicator with a displacement precision of 1 μm was used to measure the displacement of the valve poppet under different axial loads. Because the valve poppet is regarded as a rigid body, the measured displacement can be considered to be the compression between poppet and seat. The results of the compression tests are presented in Fig. 5, which are in reasonable agreement with the FEA results. The differences of 9% and 12% in displacement at the maximum compressive force are observed for the conforming contact model and nonconforming contact model between the experimental results and the FEA results, respectively.

During the high-pressure sealing performance experiments, the valve poppet was compressed against the seat by a relatively

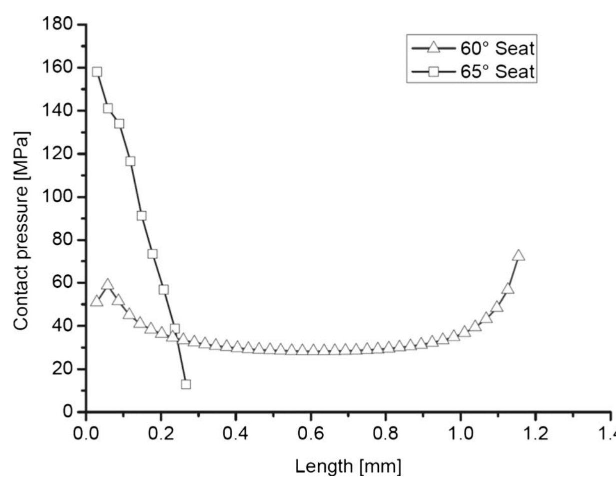

Fig. 8 Contact pressure distributions along the contact faces. The location of $x=0$ is the lower start point of the seat's cone face. Compressive forces are 320 N and 327 N for seats of 60 deg and 65 deg cone angles, respectively.

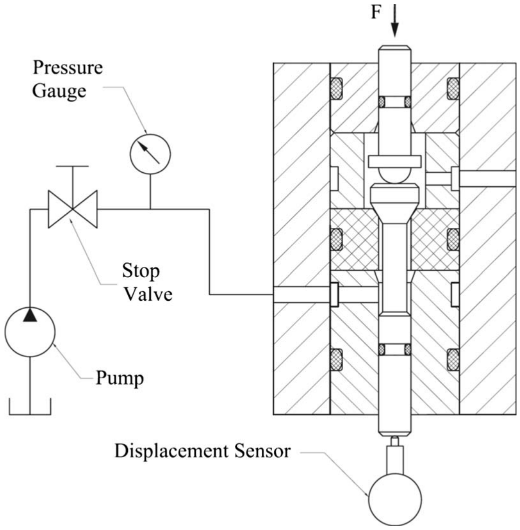

Fig. 9 Schematic illustration of the valve experiment system

greater force to ensure nonleakage sealing in the beginning. Then the pump forced high-pressure water against the inlet port of the valve. After the pressure reached the desired value, the pump and the stop valve were closed. Then the force exerted on the poppet was gradually decreased until valve leakage was detected. As a

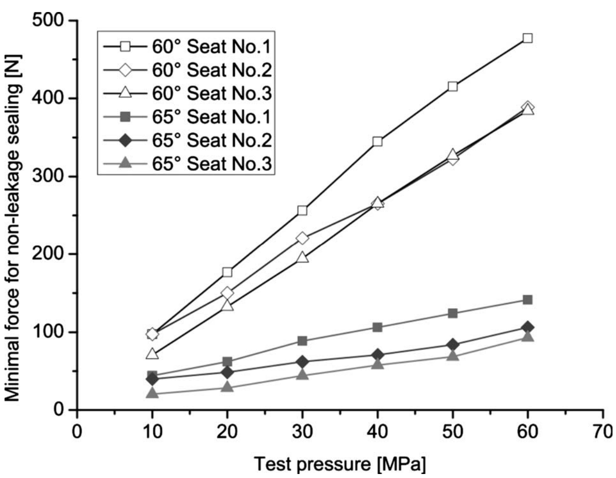

Fig. 10 Experimental results of the sealing performance of the cone valve. For the conforming poppet-seat contact model, the cone angle of the seat is 60 deg, and for the nonconforming poppet-seat contact model, the cone angle of the seat is 65 deg.

Table 1 Sea trial results of the gas-tight sampler with the new cone valve

Site	Depth (m)/pressure (MPa)	Recovery pressure (MPa)
Rainbow	2263/23.2	22.8
Lost City	744/7.6	7.5

result, the minimal forces for nonleakage sealing under different test pressures were obtained. In order to examine and compare the sealing performance between the conforming contact model and the nonconforming contact model, six sets of experiments were undertaken. As shown in Fig. 10, in comparison with the conforming contact model, the nonconforming contact model requires a much smaller force for nonleakage sealing. Accordingly, the nonconforming model is more suitable for reliable high-pressure nonleakage sealing applications.

As an application in deep-sea research, the new cone valve was used as the sampling valve in a gas-tight hydrothermal fluid sampler and tested at hydrothermal vent sites along the Mid-Atlantic Ridge during the KNOX18RR cruise from 9 July to 12 August 2008. The gas-tight sampler was deployed by the remotely operated vehicle (ROV) *Jason* at the vent sites of Rainbow and Lost City hydrothermal fields with depths of 2263 m and 744 m, respectively (refer to Refs. [13,14] for more information about the vent sites) (Fig. 11). Hydrothermal fluids were collected and maintained at almost in situ pressure after recovery (Table 1). The results from the sea trial prove that the new cone valve has an excellent sealing performance and is suitable for deep-sea gas-tight water (hydrothermal fluid/seawater) samplers.

6 Conclusions

A new high-pressure cone valve has been designed for deep-sea gas-tight water samplers. Two kinds of valve models, a conforming poppet-seat contact model and a nonconforming poppet-seat contact model, were tested to determine the sealing performance of the cone valve. From the FEA results, it was determined that the nonconforming poppet-seat contact model has a relatively larger deformation, which allows for a better mating surface between valve poppet and seat. Furthermore, it has a much higher contact pressure on the interface in comparison with the conforming poppet-seat contact model. Results from laboratory experiments show a reasonable agreement with the FEA results and indicate that the nonconforming poppet-seat contact model has a better sealing performance than the conforming poppet-seat contact model. Finally, the sea trial results prove that the new nonconforming cone valve is suitable for deep-sea gas-tight water samplers.

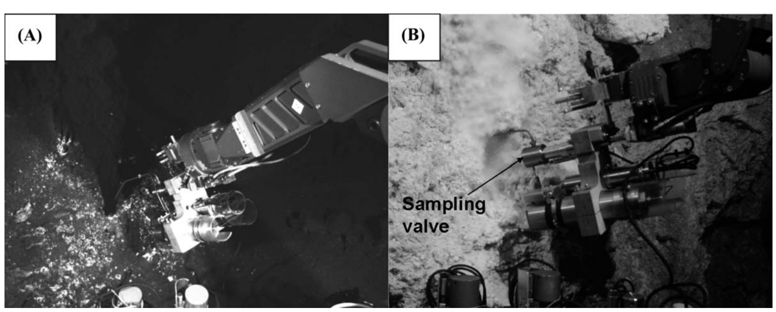

Fig. 11 Application of the new cone valve in a gas-tight sampler for collecting hydrothermal fluids. Panel A: sampling at a vent of Rainbow hydrothermal field. Panel B: sampling at a vent of Lost City hydrothermal field.

Acknowledgment

The authors thank Dr. Kang Ding, Dr. Fan Ding, and Dr. Shilun Li for their advice. We are very grateful to the crews of the R/V *Roger Revelle* and the ROV *Jason* for their kind support during the sea trial. Language editing of the manuscript by International Science Editing is also appreciated. This work was supported by the National High Technology Research and Development Program under Grant No. 2006AA09Z215 and the China National Science Foundation under Grant No. 40637037.

References

[1] Seewald, J. S., Doherty, K. W., Hammar, T. R., and Liberatore, S. P., 2002, "A New Gas-Tight Isobaric Sampler for Hydrothermal Fluids," Deep-Sea Res., Part I, **49**, pp. 189–196.
[2] Huang, Z. H., Liu, S. J., and Chen, Y., 2006, "Accumulator-Based Deep-Sea Microbe Gastight Sampling Technique," China Ocean Eng., **20**(2), pp. 335–342.
[3] Bianchi, A., Garcin, J., and Tholosan, O., 1999, "A High-Pressure Serial Sampler to Measure Microbial Activity in the Deep Sea," Deep-Sea Res., Part I, **46**, pp. 2129–2142.
[4] Chen, Y., Wu, S. J., Xie, Y. J., Yang, C. J., and Zhang, J. F., 2007, "A Novel Mechanical Gas-Tight Sampler for Hydrothermal Fluids," IEEE J. Ocean. Eng., **32**(3), pp. 603–608.
[5] Victrex Inc., 2009, Victrex PEEK Properties.
[6] Liu, W., Yang, C. J., Wu, S. J., Xie, Y. J., and Chen, Y., 2008, "Design of Novel High Pressure-Resistant Hydrothermal Fluid Sample Valve," Chin. J. Mech. Eng., **21**(01), pp. 72–76.
[7] Bergada, J. M., and Watton, J., 2004, "A Direct Solution for Flowrate and Force Along a Cone-Seated Poppet Valve for Laminar Flow Conditions," Proc. Inst. Mech. Eng., Part I: J. Syst. Control Eng., **218**, pp. 197–210.
[8] Lutkiewicz, P., and Rathjen, Ch., 2008, "Finite Element Modeling and Experimental Validation of the Sealing Mechanism of the ConFlat® Joint," J. Vac. Sci. Technol. A, **26**(3), pp. 537–544.
[9] Mathan, G., and Siva Prasad, N., 2008, "A Study on the Sealing Performance of Flanged Joints With Gaskets Under External Bending Using Finite-Element Analysis," Proc. Inst. Mech. Eng., Part E: J. Process Mech. Eng., **222**, pp. 21–29.
[10] Murali Krishna, M., Shunmugam, M. S., and Siva Prasad, N., 2007, "A Study on the Sealing Performance of Bolted Flange Joints With Gaskets Using Finite Element Analysis," Int. J. Pressure Vessels Piping, **84**, pp. 349–357.
[11] Bouzid, A. H., 2009, "On the Effect of External Bending Loads in Bolted Flange Joints," ASME J. Pressure Vessel Technol., **131**, p. 021201.
[12] Alghamdi, A. A., and Al-Sannaa, M. S., 2004, "Two-Dimensional Finite Element Analysis for Large Diameter Steel Flanges," ASME J. Pressure Vessel Technol., **126**, pp. 399–403.
[13] Früh-Green, G. L., Kelley, D. S., Bernasconi, S. M., Karson, J. A., Ludwig, K. A., Butterfield, D. A., Boschi, C., and Proskurowski, G., 2003, "30,000 Years of Hydrothermal Activity at the Lost City Vent Field," Science, **301**, pp. 495–498.
[14] Marques, A. F. A., Barriga, F., Chavagnac, V., and Fouquet, Y., 2006, "Mineralogy, Geochemistry, and Nd Isotope Composition of the Rainbow Hydrothermal Field, Mid-Atlantic Ridge," Miner. Depos., **41**, pp. 52–67.