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EVALUATION OF FRACTURE PROPERTIES TEST METHODS FOR HYDROGEN SERVICE

ASME STANDARDS TECHNOLOGY, LLC

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FOREWORD

This report evaluates testing methods on the measurement of fracture properties for design of ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (ASME BPVC VIII-3) pressure vessels for hydrogen service.

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ABSTRACT

Recommendations for appropriate testing procedures for measurement of the threshold stress intensity for fracture initiation in hydrogen, K_{TH}, and for the threshold stress intensity range for fatigue crack initiation in hydrogen, ΔK_{TH}, are provided. This includes specifics on the type of loading, loading rate, specimen size, etc, for K_{TH} tests. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are provided. Development of standards for determination of K_{TH} and ΔK_{TH} in hydrogen is encouraged. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.

To obtain conservative estimates of K_{TH} in hydrogen, it is necessary to actively load a fracture mechanics specimen in hydrogen. Testing with concurrent straining and hydrogen exposure, i.e. rising load testing, is recommended for measuring K_{TH} for steels in hydrogen. Guidelines in ASTM E1820 should be followed to determine specimen size. The loading rate that produces the lowest measured K_{TH} will vary among steels, but will be on the order of 0.1MPa√m/min (0.09 ksi√in/min).

For fatigue testing, the test frequency and the R-ratio should adequately reflect the actual loading conditions expected in vessels during service, but also be realistic for laboratory test conditions. Fatigue crack growth rates in hydrogen are affected by loading frequency. The frequency selected for fatigue crack growth rate testing in hydrogen must balance the conflicting issues of test duration and data reliability. A frequency near 0.1 Hz appears to be a reasonable value for testing quenched and tempered steels in hydrogen.

Increasing R-ratio results in increased fatigue crack growth rates when plotted versus ΔK. Data from various sources are in agreement that testing at higher R-ratios produces faster crack growth rates than testing at low R-ratios. An R-ratio of at least 0.8 is needed to produce conservative crack growth data. This is also true in the threshold region.

Crack growth rates in the treshold region are higher in hydrogen than in moist air. It is likely that tests in hydrogen produce faster crack growth rates and lower ΔK_{TH} values because they do not allow oxidation at the crack tip, which produces a crack closure effect, reducing the effective ΔK at the crack tip. A threshold value ΔK_{TH} = 2 MPa√m (2.2 Ksi√in) is suggested for inclusion in the ASME BPVC VIII-3 for hydrogen vessel design.

1 INTRODUCTION

Vessels designed for hydrogen service for ASME BPVC VIII-3 require threshold stress intensity factor and fatigue crack growth rate data. The purpose of this report is to survey the existing literature and provide guidance on the adequacy of the testing procedures provided in the above Code to measure these properties.

2 SCOPE

A literature survey was performed to locate published articles on measurement of the following properties of pressure vessel steels in hydrogen:

(a) Threshold stress intensity factor, K_{TH}. This is defined as the stress intensity factor below which a crack will not propagate when subjected to hydrogen gas at the design pressure.

(b) Fatigue crack growth rate, $da/dN=C(\Delta K)^m$. The values of the constants C and m are measured in hydrogen gas at the design pressure.

Recommendations for specific details of appropriate testing procedures for the measurement of K_{TH} are provided. This includes specifics on the type of loading, loading rate, specimen size, etc. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are also provided. Variables such as temperature, pressure and humidity are not addressed; other forms of hydrogen damage are not included.

The feasibility of a safety factor approach for the adjustment of the da/dN data from experiments to correspond to actual design parameters could not be specified because of the lack of full-scale test data. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.

2.1 Measurement of K_{TH}

Current testing procedures (paragraph KD-1045 ASME BPVC VIII, Div. 3) allow the determination of K_{TH} by either constant displacement or constant load testing of fatigue precracked specimens. A review of these procedures and of the rising load test procedure is presented below. The available literature has been searched for the following information:

(a) Static constant load or displacement vs. rising load test data

(b) Effect of exposure time on static tests

(c) Effect of strain or loading rate on rising load test

(d) Effect of specimen size on both test methods

(e) Application of static and rising load test data to actual pressure components in the presence of a crack.

A critical evaluation has been made of the existing test procedures specified in ASTM and ISO standards for measurement of K_{TH} in hydrogen. The existing K_{TH} test data for pressure vessel and piping steels in hydrogen has been compiled and compared. The literature was searched for full-scale test data to compare with properties obtained using the above-defined test procedures. No full-scale test data were found.

2.2 Measurement of da/dN

The available literature has been searched for information on the effects of test frequency, shape of the load-time cycle, and R-ratio on threshold fatigue crack growth rate, as follows:

(a) The appropriate test frequency and R-ratio to be used in da/dN measurements are suggested. The test frequency and the R-ratio should adequately reflect the actual loading conditions expected in vessels during service, but are also be realistic for laboratory test conditions. No data was found for shape of the load-time cycle.

(b) The effect of R-ratio on da/dN has been evaluated.

(c) A value of ΔK_{TH} for Q&T steels has been identified for inclusion in the ASME BPVC VIII-3 for hydrogen vessel design.

2.3 Recommendations

Recommendations for specific details of appropriate testing procedures for the measurement of K_{TH} are provided. This includes specifics on the type of loading, loading rate, specimen size, etc. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are provided. The feasibility of a safety factor approach for the adjustment of the da/dN data from experiments to correspond to actual design parameters could not be specified because of the lack of full-scale test data. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.