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Toughness trends under dynamic and cyclic loading on nuclear steels

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ABSTRACT

One of the key aspects of the IPIRG programs was to assess the effects of pipe fracture behavior under seismic loading. Seismic loading involved not only pipe system considerations, but also dynamic and cyclic load effects on the material properties at service temperatures. Large-scale pipe experiments and laboratory-sized fracture specimen experiments were conducted to study the effect of dynamic and cyclic loading on the fracture toughness on nuclear piping materials. The results presented show that both dynamic and cyclic loading can have effects on the toughness of nuclear piping materials, and that there were no interactions between the two. The combined effect could be predicted from the individual effects.

INTRODUCTION

In many fracture mechanics applications, quasi-static, monotonic J-R curves are often used in analyses to predict the load-carrying capacity of cracked piping systems that are subjected to seismic events, which are dynamic and cyclic in nature. However, the quasi-static, monotonic properties of most nuclear piping materials do not accurately represent the true fracture behavior under dynamic and cyclic loading. To attempt to understand these effects, the First and Second International Piping Integrity Research Group programs (IPIRG-1, Ref. 1 and IPIRG-2, Ref. 2) were conducted to study and document the effects of dynamic and cyclic loading on the behavior of nuclear piping materials. In these programs, both large-scale piping experiments and small-scale material property experiments were conducted.

The objective of this paper is to document the effects of both dynamic and cyclic loading on the toughness of the nuclear piping materials investigated in these programs. Both ferritic and austenitic nuclear piping base materials and submerged-arc weld materials were tested. The pipe experiments and the material property specimens were conducted at 288 C (550 F).

EXPERIMENTS

In the IPIRG-1 and IPIRG-2 programs, both full scale pipe experiments and material property specimen experiments were conducted to study the effect of dynamic and cyclic loading on the toughness of nuclear piping steels. A series of displacement-controlled cyclic-load TWC pipe tests were conducted on both stainless steel (TP304, Battelle designation DP2-A23) and carbon steel (A106 Grade B, Battelle designation, DP2-F30) 6-inch nominal diameter Schedule 120 pipes. The pipe tests were conducted at stress ratios of 0 and -1 with quasi-static and dynamic loading rates. Dynamic loading refers to loading rates comparable to those in high amplitude seismic events, i.e., 2 to 4 Hz. Full details of these tests can be found in Reference 1.

In addition to the pipe experiments a series of cyclic-loaded compact tension specimen experiments were conducted. In order to compare the behavior of cyclic-loaded and dynamic-loaded C(T) specimens with that of cyclic-loaded and dynamic-loaded TWC pipe tested in the IPIRG-1 program, the base metal materials selected for the C(T) specimens were the same as those used in the pipe tests. In addition to the base metal experiments, submerged-arc welded specimen experiments were conducted.

The cyclic C(T) experiments were conducted at a variety of stress ratios (-1, -0.8, -0.6, -0.3, 0) and plastic displacement increments, δ_{cyc}/δ_i (0.1, 0.025, 0.2). δ_{cyc} is the displacement per cycle and δ_i is the load-line displacement at crack initiation in a monotonic test. All of the base metal cyclic-load specimens were run at quasi-static loading rates (approximately 10 min. to crack initiation). Half of the weld specimens were run with quasi-static rates and half were run at dynamic rates. For the dynamic experiments, the rate was chosen to be 4 Hz. Since these experiments are increasing amplitude tests at a constant ramp rate, an average of 4 Hz was used.

In order to determine the extent of toughness degradation due to cyclic and dynamic loading, an estimate for the J-integral has to be made for these specimen geometries. For C(T) specimens under monotonic loading, estimations of J have been made and published in ASTM 1152, Standard Test Method for Determining J-R curves. However, classical J, based on deformation theory, is undefined when unloadings occur. Therefore, an engineering approximation of J was required to assess the cyclic effects on fracture toughness. In the IPIRG-1 and IPIRG-2 programs, cyclic J-R curves were calculated from the upper envelope of the experimental load-displacement record using the η-factor approach. Details of these analyses can be found in Reference 1 and 2.

DYNAMIC, MONOTONIC LOADING

Figure 1 shows the fracture toughness ratio for both material types as a function of the material's yield-to-ultimate strength ratio. In this figure, the dynamic values of J are normalized by the quasi-static values at both crack initiation and at a crack extension equal to 30 percent of the original ligament. Included in this figure are both base metal and weld metal materials. A trend seems to be forming that as the yield-to-ultimate-strength ratio is increased, the dynamic J-R curve also increases as compared to the quasi-static J-R curve. However, there are some materials that do not follow this trend, i.e., a TP304 elbow (IP2-AE1) and a Japanese STS410 TIG weld (IPF16W). For the carbon steel, the trend suggests that if a metals yield-to-ultimate strength ratio is greater than 0.5, the dynamic J-R curve will be equal to or greater than the monotonic J-R curve. However, most carbon steel nuclear piping base metal materials have a yield-to-ultimate strength ratio less than 0.5 and will show a detrimental effect of the J-R curve with increasing strain rate. Interestingly, the A106B carbon steel SAW (F29W) tested showed a large increase in resistance, but also had a yield-to-ultimate strength ratio greater than 0.5. However, the TIG weld (IPF16W) also had a yield-to-ultimate ratio greater than 0.5 but showed no change in fracture resistance with increasing strain rate. This result suggests that even though a trend may be forming there are not enough data available to make a solid conclusion about the relationship shown in Figure 1, especially for weld metals.

Figure 2 shows the same fracture toughness ratios versus a test temperature-to-room temperature Brinell hardness ratio for the carbon steel materials. This toughness ratio is taken at a crack extension equal to 30 percent of the original ligament. The technique for measuring the test temperature Brinell hardness was developed in Reference 3 and was used to determine a materials susceptibility to dynamic strain aging. This figure shows that for materials with a test temperature-to-room temperature Brinell hardness ratio greater than 1, the toughness is reduced as the loading rate is increased. Although there is a better correlation with the hardness ratio than the yield-to-ultimate strength ratio, there are some data that do not follow the hardness ratio trend. In this case, the carbon steel SAW (F29W), which had a hardness ratio just less than one, showed a large increase in toughness with increasing loading rate. It is possible that this screening criterion is not applicable to welds where perhaps different dynamic strain aging mechanisms occur than in the base metals.

QUASI-STATIC, CYCLIC LOADING

Figure 3 shows $J_{QS,cyc}/J_{QS,mono}$ as a function of stress ratio for the stainless steel investigated. The ratio $J_{QS,cyc}/J_{QS,mono}$ is a measure of the decrease in J when going from a monotonic to a cyclic loading history. In order to make a comparison between the C(T) and TWC pipe experiments, the J values were taken at a crack extension equal to 30 percent of the initial ligament. The amount J decreases with decreasing stress ratio is a function of the displacement increment. For small increments, the J value drops significantly at the intermediate stress ratios, while at large displacement increments, the decrease in J is minimal until a stress ratio of -0.8. It is possible that fatigue is playing a role in the apparent decrease in J at the smaller displacement increments. However, it is more likely that with smaller crack growth increments, the crack is growing in a more severely damaged region of material than if it was allowed to grow further during each cycle.

Each of the stainless steel TWC pipe results fall below any of the C(T) predictions in Figure 3. Therefore, for the stainless steel, the cyclic-load C(T) experiments tended to overpredict the TWC pipe $J_{QS,cyc}/J_{QS,mono}$ response at this particular crack extension. Overall, the C(T) tests did a reasonable job in predicting the decrease in toughness under cyclic loading.

Figure 4 shows the ratio $J_{QS,cyc}/J_{QS,mono}$ for the C(T) and TWC pipe experiments for carbon steel investigated. Again, note that this ratio is a measure of the relative decrease in resistance due to cyclic loading and can not be used to directly compare the cyclic-load C(T) J-R curves to the cyclic TWC pipe J-R curves. The cyclic-load C(T) results follow the same trend as the TWC pipe experimental results. This finding indicates that for this material the decrease in resistance due to cyclic loading is approximately the same for the C(T) and TWC pipe geometries.

DYNAMIC, CYCLIC LOADING

A method for estimating the combined dynamic, cyclic resistance of nuclear piping materials may be used that multiplies the quasi-static, monotonic resistance to the relative decrease in resistance due to both cyclic and dynamic effects producing an estimate of the dynamic, cyclic resistance. Dynamic, cyclic ($J_{dyn,cyc}$) quasi-static, monotonic (J_{QS}), dynamic, monotonic, (J_{dyn}) and quasi-static, cyclic (J_{cyc}) J-R curves were developed for two base metals and two weld metals. Figure 5 shows the experimental J values at some crack growth for the dynamic, cyclic experiments versus a calculated J using the quasi-static, monotonic resistance and the relative decrease in J due to cyclic and dynamic loading. In Figure 5, F_{dyn} is defined as $J_{dyn,mono}/J_{QS,mono}$ which is the ordinate in Figures 1 and 2 and F_{cyc} is defined as $J_{QS,cyc}/J_{QS,mono}$, which is the ordinate in Figures 3 and 4. Note that all J values shown in Figure 5 are taken at a crack extension of 30 percent of the original ligament, i.e., at the maximum limit of valid crack growth in the tests.

The open symbols in Figure 5 represent the results taken directly from the actual experimental data, while the solid symbols represent $J_{dyn,cyc}$ results calculated from the average of the cyclic and dynamic experimental data. The trend in Figure 5 suggests that by multiplying the percent change in the monotonic resistance due to the cyclic and dynamic loading to the quasi-static, monotonic resistance produces a good approximation of the actual resistance due to dynamic, cyclic loading. However, when the relationship (average values) between the materials' yield-to-ultimate ratio and the relative decrease in quasi-static monotonic resistance due to cyclic and dynamic loading was used, the estimates of the dynamic, cyclic resistance were higher than the experimental values. This trend suggests that with some refinement, a suitable criterion can be developed to predict the resistance under dynamic, cyclic loading using the quasi-static, monotonic properties.

CONCLUSIONS

The variable effect of dynamic loading on fracture resistance of the carbon steel materials investigated may be related to the materials susceptibility to dynamic strain aging. The DSA sensitivity may be correlated with the materials yield-to-ultimate strength, and to the high temperature to room temperature Brinell hardness ratio. The trends presented suggest that dynamically loaded carbon steel materials whose yield-to-ultimate strength ratio is greater than 0.5 will have toughness values that are equal to or higher than those obtained at quasi-static loading rates. This apparent dependency on the yield-to-ultimate strength ratio and the high temperature to room temperature Brinell hardness ratio may aid in the creation of a criterion that would characterize a material's fracture toughness response to dynamic loading. However, there was significant scatter in each of these correlations, and perhaps some combination of these parameters would produce a better correlation.

The interaction between cyclic and dynamic crack growth was investigated by comparing the J values from a dynamic, cyclic (R = -1) C(T) test to the J value from a simple quasi-static monotonic C(T) test multiplied by a dynamic correction factor (F_{dyn}) and a cyclic correction factor (F_{cyc}). F_{dyn} was the ratio of the J values from the dynamic monotonic C(T) test to the quasi-static monotonic C(T) test at the same amount of crack growth ($J_{dyn,mono}/J_{QS,mono}$). F_{cyc} was the ratio of the J values from the quasi-static cyclic C(T) test to the quasi-static monotonic C(T) test also at the same amount of crack growth ($J_{QS,cyc}/J_{QS,mono}$). The results were encouraging in that for four materials covering a wide range in toughness, the J value from $F_{cyc}*F_{dyn}*J_{QS,mono}$ was essentially identical to the J value from the dynamic, cyclic C(T) test for the same amount of crack growth. Hence, these data showed no interaction between dynamic and R = -1 cyclic loading.

ACKNOWLEDGMENTS

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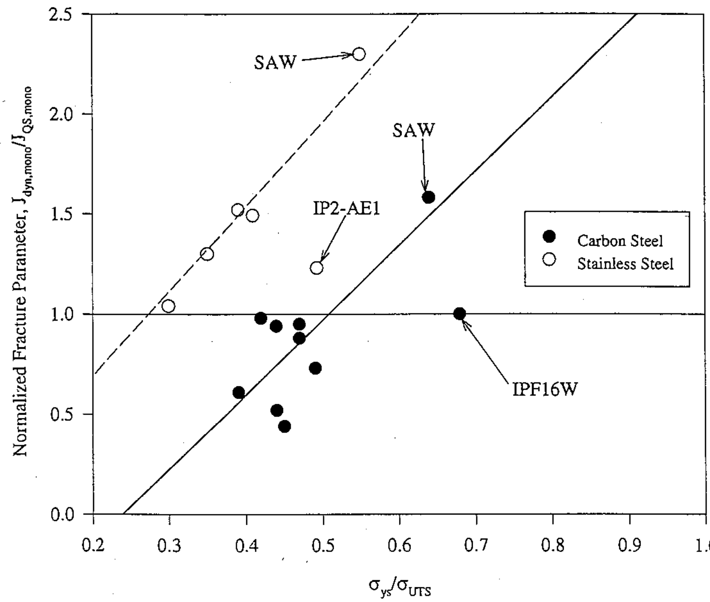

Figure 1. Normalized fracture parameter versus yield-to-ultimate ratio

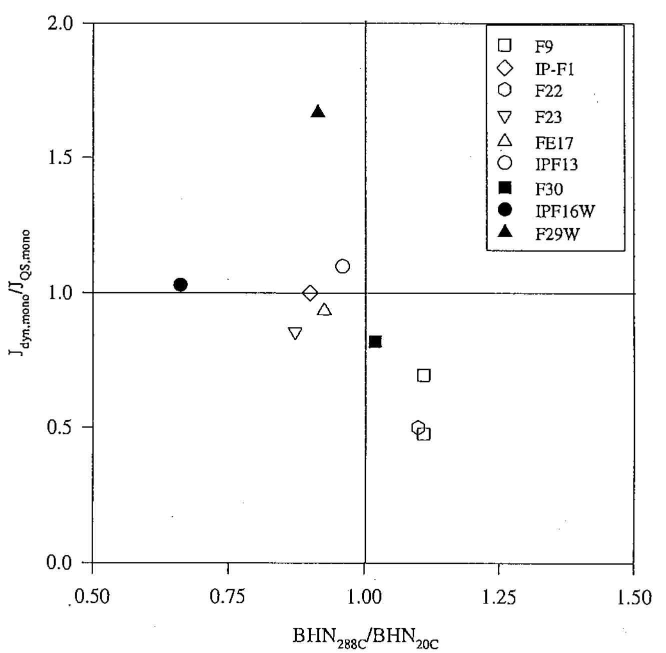

Figure 2. Fracture toughness ratio versus Brinell hardness ratio

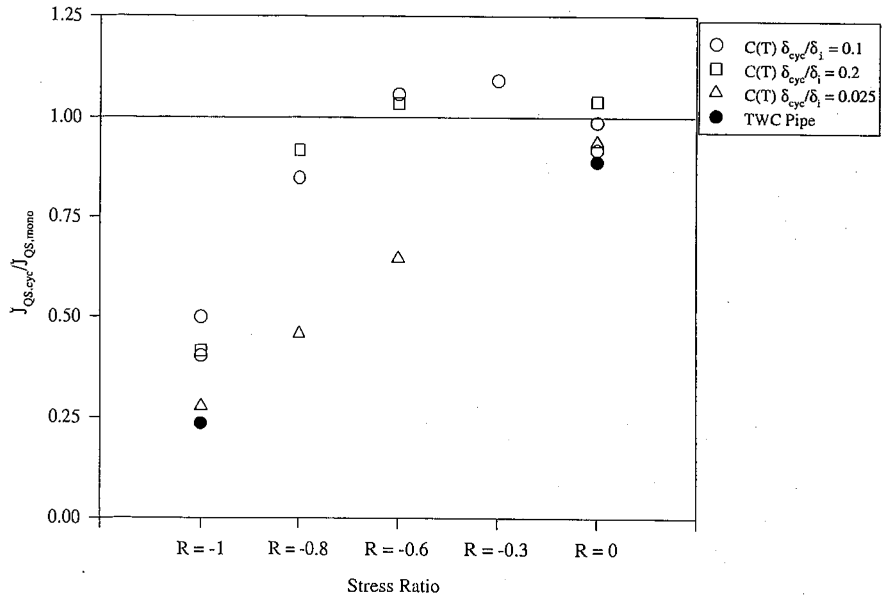

Figure 3. $J_{QS,cyc}/J_{QS,mono}$ versus stress ratio for stainless steel C(T) and pipe experiments

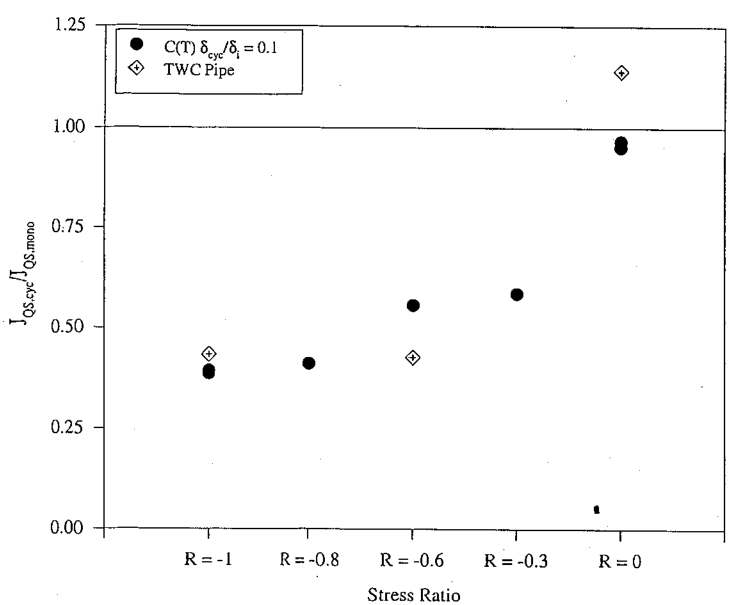

Figure 4. $J_{QS,cyc}/J_{QS,mono}$ versus stress ratio for carbon steel C(T) and pipe experiments

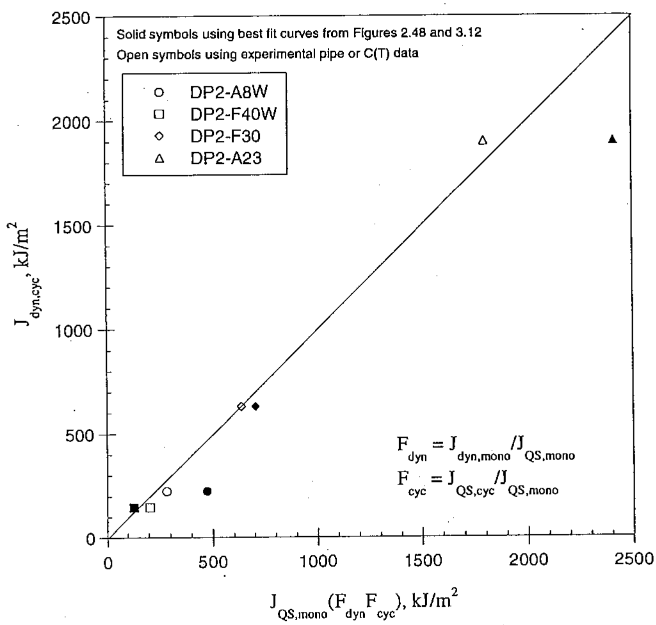

Figure 5. Experimental versus calculated J for dynamic, cyclic loading