VIBRATION FATIGUE TESTING OF SOCKET WELDS, PHASE II

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ABSTRACT

This paper describes the results of the second phase of an EPRI sponsored program to perform high cycle fatigue testing of socket welds in order to quantify the effects of various factors upon the fatigue strength. Analytical results had demonstrated that the socket weld leg size configuration can have an important effect on its high cycle fatigue resistance, with longer legs along the pipe side of the weld greatly increasing its predicted fatigue resistance. Other potentially important factors influencing fatigue life include residual stress, weld root and toe condition, pipe size, axial and radial gaps, and materials of construction. The second phase of the program tested 27 additional socket weld specimens of various designs by bolting them to a vibration shaker table and shaking them near their resonant frequencies to produce the desired stress amplitudes and cycles. Another objective of the second phase of testing was to evaluate various methods of in-situ modification or repair of socket welds, which could be used as alternatives to replacement with butt welds. The results of the program are presented which include comparisons of the various socket weld designs with standard Code socket welds, butt welds, ASME mean failure data, and recent test data published by Higuchi et al. Fatigue Strength Reduction Factors are calculated based on the testing results.

INTRODUCTION

Failures of small bore piping connections continue to occur frequently in U.S. nuclear power plants, resulting in degraded plant systems and unscheduled plant downtime. Prior research [1] has indicated that the majority of such failures are caused by vibration fatigue of socket welds. In order to better understand and characterize this phenomenon, investigations have been performed in the U.S. [1,2,3] and overseas [4,5,6]. Analytical results reported in Reference [3] have demonstrated that the socket weld leg size configuration can have an important effect on its high cycle fatigue resistance, with longer legs along the pipe side of the weld greatly increasing its predicted fatigue resistance. Other factors which potentially influence socket weld fatigue life are residual stress, weld root and toe condition, loading mode, pipe size, axial and radial gaps, and materials of construction.

The test program described in this paper was initiated in 1997 under EPRI sponsorship to study the importance of these factors. A large number of socket weld samples were vibration-fatigue tested to failure on a high frequency shaker table. The objectives of the testing were to improve the industry's understanding and characterization of the high cycle fatigue resistance of socket welds and to develop appropriate fatigue strength reduction factors for such welds reflecting the effects of those factors listed above which prove to be significant. The ultimate goal of this research is to develop recommended design and fabrication practices that can be used to enhance socket weld fatigue resistance in vibration-sensitive locations, as well as to provide guidelines for screening out and preventing vibration-fatigue failures in existing welds.

The first phase [7], completed in 1998, investigated the variation in high cycle fatigue resistance as a function of weld leg length, pipe diameter, and piping material. The effect of an additional weld pass, post-weld heat treatment, and eliminating the ASME Code-required axial gap were also studied. The test setup and results have been described in a previous paper [8]. The second phase investigated remedial actions for existing socket welds, in order to determine their effectiveness in extending the useful life of socket welded joints, in lieu of making expensive modifications. The effect of varying toe conditions was also studied in Phase II, and additional data at higher loads was collected to further quantify the benefit of increased weld leg length. This paper describes the second phase of the test program, and provides the cumulative results for both phases.

BACKGROUND AND APPROACH

The probability of fatigue failure at a weld is a function of many considerations: type of weld, weld profile, material, weld size, wall thickness, heat treatment, grinding after welding, etc. Socket welds are commonly used in small bore piping (2" and under) joints due to their ease of assembly, but their fatigue strength is generally considered to be less than that of a butt weld. The fatigue strength reduction factor (FSRF) is a means of quantifying the effect of a local structural discontinuity on the fatigue strength of the joint. It is defined as the fatigue strength of the component without the discontinuity divided by the fatigue strength with the discontinuity. The FSRF is usually determined by test, and is generally calculated by dividing the endurance limit of the ASME mean failure curve for polished bar specimens, by the endurance limit of the joint in question. The endurance limit is used because the FSRF varies with fatigue life; the value at the endurance limit is bounding. For practical reasons, the endurance limit is often defined as the fatigue strength at some large, predefined number of cycles, such as $2x10^7$. Article NB-3600 of Section III, which provides rules for the design of Class 1 piping, accounts for the variation in fatigue strength between different welds and fittings by multiplying the calculated alternating stress by stress indices, before entering the fatigue curves. For primary plus secondary bending moment loading, the applicable stress index is the product of C_2 and K_2. C_2K_2 is approximately equivalent to the FSRF, although there are some differences in derivation relating to testing requirements and statistical treatment of the data. For socket welds (1998 Edition of the Code), $C_2 = 1.93$ for a Code minimum weld according to the rules of the fabrication section (NB-4427), and the product C_2K_2 is 3.86, or about an FSRF of 4 for a socket weld.

PARAMETERS TESTED

While the ASME piping design Code provides stress indices for socket welds, these represent the predicted fatigue strength of standard weld designs. This test program included welds of the standard Code design as well as several variations in weld design. The following is an overview of the parameters that were tested.

Weld Leg Size

Analysis described in Reference 3, and testing reported in Reference 10, have identified variations in socket weld design that can significantly affect the fatigue life of the joint under high cycle loading. One of the most important factors is the weld leg size. Extending the weld leg length along the pipe side of the weld by a factor of two over the Code minimum of 1.09 t_n (where t_n is the nominal pipe wall thickness) has resulted in a significant improvement in fatigue resistance. In this testing program, the effect of weld size on fatigue resistance was studied by testing samples fabricated with oversized legs on the pipe side, and comparing them to control samples at nominal Code dimensions. Testing was also done to study how conventional small bore butt welded fittings compare to new 2 x 1 welds, and to 1 x 1 welds modified to 2 x 1 weld dimensions, under comparable loading conditions. The butt welded specimens consisted of pipes welded to standard weld neck flanges, which is similar to a typical method used in power plants for upgrading socket welded fittings when vibration problems have occurred.

Weld Modification and Repair

An important purpose of the testing program was to study repair or modification actions that could be taken to improve the fatigue resistance of an existing socket welded joint. Repair concepts for leaking socket welds that would allow plants to continue operating until the next outage before implementing a permanent repair were also tested. Weld overlay repairs were applied to four of the welds that developed leaks in the first phase of testing. The leaks were peened with water still in the pipe, and a seal weld was applied when the leak stopped. The overlay design applied sufficient additional reinforcement to cover the possibility of either a toe or a root failure having occurred. The design is shown in Figure 3. The weld was applied using a shielded metal arc welding process to simulate the most likely welding process that would be used for a temporary repair in a power plant. The pipe side toe of the weld did not have a blending radius, producing a sharp transition, as would likely be found in a field repair. The repaired welds were tested at their original load levels to determine if they could survive until the next outage, or convenient time for a permanent repair. Specimens chosen for these tests included carbon and stainless steel welds that had experienced root and toe failures.

Another remedial approach tested was to modify existing standard Code welds to a 2 x 1 leg length configuration after having been fatigue cycled in their original configuration but before any obvious cracking or fatigue damage was observed. This is illustrated in Figure 2. Testing compared the degree of improvement for the modified welds relative to new 1 x 1 and 2 x 1 welds.

Weld Profile and Toe Condition

The profile of the weld and the condition of the weld toe can have a significant effect on socket weld fatigue life. The ideal toe condition is for the weld to blend smoothly with the pipe with no discontinuity or undercut. Premature toe failures are generally the result of a discontinuity or small flaw in the toe, which propagates through the base metal. Grinding the weld can help by removing small surface imperfections, which could be sites for crack initiation. Conversely, heavy "abusive" grinding can worsen the situation by leaving a cold worked condition and tensile residual stresses. In the first phase of testing, several specimens exhibited toe failures prior to the expected number of cycles. When toe failures occurred, they were generally associated with minor welding discontinuities at the toe, which would normally be acceptable by Code workmanship standards. In the second phase, samples with polished toes, as-welded toes, and intentionally poor toes were tested to quantify the effect of the toe condition. One of the butt welds was also fabricated with a toe defect to see if this is a concern for butt welds.

Residual Stress

The residual stress in the weld can have an important effect on fatigue life in the high cycle regime. Residual stress acts as a mean stress, which reduces the allowable number of cycles at a particular alternating stress. This is more important in the high cycle region than in low cycle fatigue, where the effects of plasticity act to relieve the mean stress. The residual stress in a socket weld can be altered by varying the welding technique, such as by adding a final cover weld pass. "Last Pass Improvement" refers to a technique in which a normal Code socket weld is improved by adding a last pass on the pipe side of the weld, which changes the residual stress in the weld root to compressive and extends the leg length along the pipe somewhat. Tests were conducted to determine the amount of benefit gained by this process.

Post-Weld Heat Treatment

Post-weld heat treatment (PWHT) is another method of reducing the residual stress in a weld. The ASME Code requires PWHT for most ferritic steel welds, but exempts socket welds and austenitic steels. One of the reasons is that heating austenitic steels can sensitize them to intergranular stress corrosion cracking (IGSCC). However, in view of the importance of residual stresses in high cycle fatigue life, applying PWHT to socket welds in vibration sensitive locations that are not exposed to an IGSCC conducive environment can be a viable means of reducing residual stress.

Axial Gap

The ASME Code requires that an axial gap of 1/16" be provided between the pipe end and the socket. The reason is that if the pipe carries hot fluid, differential thermal expansion between the pipe and the fitting may add significant stress to the weld if there is no gap. Also, without the gap, shrinkage of the fillet weld could produce residual stresses in the weld, pipe, and fitting wall. However, some recent testing [4] has indicated that absence of the gap has a negligible effect on fatigue life.

Pipe Size

The ASME Code design fatigue curves do not reflect any differences in fatigue strength as a function of pipe diameter. However, the Phase 1 testing showed that ¾" pipe had superior fatigue strength to the

Piping Material

Although the endurance limit of carbon steel is lower than that of stainless, previous test data has indicated that some of the fatigue strength reduction factors for stainless steel are higher. While the majority of the samples tested in this program were stainless steel, one-third of the 2" specimens were carbon steel. The purpose was to note whether any of the modifications to socket weld design are more or less effective in carbon steel than in stainless.

TESTING ARRANGEMENT

The test setup was previously described in detail in [8]. The testing method used specimens vertically cantilevered on a shaker table. All specimens were fabricated from Schedule 80 piping and compatible components. Loading amplitudes were selected based on fatigue data available in the literature, with the target of generating failures in approximately 10^6 to 10^7 cycles. As a large number of runouts (tests ended without failure) were obtained in the first phase of testing, the stress levels in the second phase of testing were increased.

Sets of nine socket weld specimens were bolted to the shaker table and shaken simultaneously near their resonant frequencies to produce the desired stress amplitudes and cycles. A cantilevered specimen of the type illustrated in Figure 1 was used, with the test weld being the weld at the lower end of the specimen between the pipe and the flange used to bolt the specimen to the table. Different load amplitudes were applied to different samples in the same test by fine tuning the specimen natural frequencies relative to the shaker table excitation frequency. The shaker table typically ran at 100-110 Hz and the test specimens had natural frequencies that were nominally 4-8 Hz lower than the excitation frequency. By adding or subtracting small masses, such as nuts and washers, the frequencies of the test specimens were moved enough off resonance to adjust each individual response acceleration. The flange configurations were modified to produce socket weld details typical of the socket welded fittings used on small bore piping in nuclear plants (tees, elbows, weldolets, couplings, etc.). The specimens were pressurized with air to a moderate pressure of approximately 50 psig. When depressurization occurred, indicating a failure, the specimen was removed from the table at the next convenient test stoppage, and the testing was then resumed with only the remaining specimens. This test method is directly comparable with the plant loading mechanism of concern (vibration fatigue), whereas conventional fatigue testing techniques (rotating beam or four point bending) can have considerable variability with respect to each other [5,6], and possibly with respect to in-plant vibration.

The stress in the test sample was determined from the measured acceleration response and test frequency, using beam formulas superimposing the concentrated weight and distributed weight effects. Nominal pipe wall but actual lengths and weights were used. It was observed that when the crack formed, the natural frequency of the specimen reduced, causing the acceleration response and the resulting stress to decline (this usually affected only the last 3-5% of the cycles). The stress reported in the test results is an average over all of the cycles.

TEST RESULTS

Table 1 is a summary of the results of the Phase II tests. The Phase I results have been reported previously in [8]. However, the results of both phases of testing are plotted in Figures 4-8. Trend curves from socket weld fatigue testing reported in [4,5,6] are also shown on the plots, labeled "Higuchi

ME mean failure curves for polished bar specimens are also shown for comparison purposes. When specimens exhibited toe failures (solid points in the figures) they tended to fail somewhat prematurely, relative to the more common root failures.

Table 1 - Phase II Test Results

Test Series 4 – Repairs and Mods. - 2" SS and CS			
Specimen	Sa(ksi)	Nf	Comments
1 – Mod. to 2x1 SS	17.4	2.57E+07	Runout
2 – Mod. to 2x1 SS	17.6	5.05E+06	Toe Failure
3 – Prev. Runout SS	16.3	1.33E+07	Root Failure
4 – Mod. to 2x1 CS	14.7	2.57E+07	Runout
5 – Mod. to 2x1 CS	11.1	2.57E+07	Runout
6 – Weld Repair CS	8.9	2.57E+07	Runout
7 – Weld Repair CS	8.0	2.57E+07	Runout
8 – Weld Repair SS	11.6	1.10E+07	Failure at Orig. Toe
9 – Weld Repair SS	11.0	2.57E+07	Runout
Test Series 5 – Toe Conditions - 2" SS			
Specimen	Sa(ksi)	Nf	Comments
1 – Smooth Toe	24.2	1.26E+06	Toe Failure
2 – Smooth Toe	23.6	1.04E+06	Toe Failure
3 – Poor Toe	18.2	1.62E+06	Toe Failure
4 – Poor Toe	20.5	3.80E+05	Toe Failure
5 – Polished Toe	21.4	3.24E+05	Toe Failure
6 – Polished Toe	22.5	9.10E+05	Root Failure
7 – Smooth Last Pass	22.8	3.56E+05	Toe Failure
8 – Smooth Last Pass	23.3	1.62E+06	Root Failure
9 – Smooth Last Pass	22.0	1.96E+06	Root Failure
Test Series 6 – 2x1 vs. Butt Weld - 2"			
Specimen	Sa(ksi)	Nf	Comments
1 – Butt Weld SS	23.0	1.22E+06	I. D. Root Failure
2 – Butt Weld SS	22.3	6.61E+05	I. D. Root Failure
3 – Butt Weld CS	15.3	2.19E+06	Toe Failure
4 – Butt Weld CS	16.8	1.97E+06	Toe Failure
5 – Butt SS Undercut	22.6	1.00E+06	Toe Failure
6 – 2x1 SS	24.0	1.04E+06	Toe Failure
7 - 2x1 SS	23.5	2.11E+07	Runout
8 – 2x1 CS	16.5	2.38E+06	Root Failure
9 – 2x1 CS	16.9	3.75E+06	Root Failure

In general, failures at a lower number of cycles and/or higher stress tended to originate at the toe while the higher cycle / lower stress failures tended to occur at the root.

The following sections describe in detail the test results for each of the parameters studied.

<u>Effect of Weld Size</u>

Figures 4 and 5 show the results of testing of standard Code size welds (1 x 1) and enhanced, 2 x 1 welds, which have a leg dimension along the pipe of twice that of the Code minimum leg dimension. Also shown for comparison are the test results for the butt welds. Figure 4 shows the 2" stainless steel data; Figure 5 shows the 2" carbon steel data. In general, the nominal Code dimension (1 x 1) specimens yielded data somewhat above the corresponding "Higuchi Curve". The failures at the lower numbers of cycles were toe failures and those at higher cycles were root failures (open points in the figures). The two butt weld failures at low cycles in this figure originated in the inside diameter of the pipe, at the edge of the weld root.

The 2 x 1 specimens were significantly stronger than the standard welds. All exhibited runouts at the lower stress levels, even though tested at stress amplitudes 30% higher than those applied to the standard Code specimens. At the higher stress levels, in the stainless steel tests, one was a runout at 23.5 ksi, while the other failed at only 1×10^6 cycles, and 24 ksi. The latter specimen was a toe failure, however, and performed about the same as the standard Code specimens tested at this stress level, which also exhibited toe failures. In the carbon steel tests at higher stress levels, both of the 2 x 1 welds performed significantly better than the standard welds.

The butt welds were tested for the purpose of comparison against the 2 x 1 welds. However, the butt welds did not perform as well as expected. In the stainless steel tests, they were about as strong as the standard Code socket welds, while in the carbon steel tests, they were somewhat better than the standard welds, but not quite as good as the 2 x 1 welds. The butt weld results can be explained by the fact that the tests were comparing a socket welded flange to a butt welded, weld neck flange, and not to a pipe-to-pipe butt weld. The weld neck flange acts as a tapered transition, and the ASME Code stress indices reflect a reduced fatigue strength for such a joint. For the as-welded standard socket weld (1998 Code), $C_2K_2 = 3.86$; for the as-welded butt welded transition, $C_2K_2 = 3.78$. For an as-welded pipe-to-pipe butt weld, $C_2K_2 = 2.57$. Thus the stress indices for the butt welded transition are only slightly better than that of a socket weld. Socket welds are rarely used in pipe-to-pipe connections but rather at elbows, branch connections, or other fittings which would result in thickness transitions even if replaced with butt welds. Therefore the practice of replacing socket welds with butt welds to "fix" vibration fatigue problems appears to be of little value, if the butt weld is to a fitting with a geometric transition.

Two of the stainless steel butt welds failed by a crack that originated at the inside diameter of the pipe, at the edge of the weld root. The crack grew perpendicular to the pipe axis, through the weld metal. Further examination of the weld root indicated the presence of a number of discontinuities, which may have served as crack initiation sites. The other stainless steel butt weld had an undercut intentionally placed at the toe; although the specimen failed at the toe, the fatigue strength was equivalent to the other butt welds.

It was concluded from these tests that the 2 x 1 welds offer a significant improvement in fatigue strength over standard Code welds. They also provide a greater strength improvement than replacement with butt welded fittings, in addition to easier fitup and construction.

Toe Condition

The results of testing the three different toe conditions are shown in Figure 6. The poor toe conditions produced failures at or below the Higuchi data curve. As expected, they were toe failures. It is interesting to note that the two polished toe specimens did not show any improvement over the smooth, as-welded pieces. One of the polished toes failed at the toe right on the Higuchi trend line, which was below all of the standard, as-welded samples. Examination of the fracture surface under magnification showed multiple crack initiation sites along the scratch marks generated by the polishing. It is concluded from these tests that while a poor toe condition definitely reduces the fatigue life, polishing the toe does not seem to improve it. Possibly using a finer grit sandpaper and polishing in the axial direction would have produced better results. Four of the five specimens with a final weld pass at the toe performed somewhat better than the standard welds, with one failing early near the Higuchi curve.

Weld Process Enhancements

Figure 7 compares the results of the weld process enhancements for 2" stainless socket welds. Figure 8 shows the same for the carbon steel tests. The enhancements were: adding a "last pass" at the weld toe on the pipe side to improve the residual stress; post-weld heat treatment of the weld; and eliminating the Code required axial gap. The testing results for these specimens were previously reported in [8]. The last pass improved specimens yielded somewhat mixed results. In general, where premature failures occurred in last pass improved specimens, they were due to toe failures, indicating that the last pass welding may have left a discontinuity or stress raiser at the toe. Three of the five last pass samples performed better than the standard socket welds. Post weld heat treatment appears to increase the fatigue life of the standard Code specimens. One of the stainless steel runouts from Phase I was retested at a higher load in test series 4. Despite having withstood 23 million cycles at 12 ksi, it lasted another 13 million cycles at 16 ksi. The ASME Code required gap appears to have no effect on high cycle fatigue resistance.

Modified and Repaired Welds

Two stainless steel and two carbon steel 1x1 socket welds that had been tested to runout in the second or third test series had additional weld metal applied to them to make them 2x1 welds. The modified welds were then retested at loads that were approximately 50% higher than in the previous tests. The purpose was to determine whether an existing Code standard weld can be increased to a 2x1 weld in situ to improve its fatigue strength, and how it would compare against a new 2x1 weld. The results are shown on Figures 4 (stainless) and 5 (carbon steel). One of the stainless welds was a runout at 17.4 ksi. The other failed at the toe after 5 million cycles at 17.6 ksi. The first specimen was a former Code standard weld, and the second was a post-weld heat treated specimen. It should be noted that the latter weld was sectioned, and examinations indicated that the original weld did not have any indications of cracking prior to the buildup. Both of the carbon steel welds were runouts, the first being a former post-weld heat treated specimen tested at 14.7 ksi, and the second, a no-gap specimen tested at 11 ksi. The results clearly show an improvement in fatigue strength over standard Code welds. As for comparing the built up 2x1 welds with new 2x1 welds, most of the welds of both categories were runouts, so a definitive comparison was not possible. However, the built up welds appear to be at least as good as the new 2x1 welds.

The results of the tests of the weld overlay repaired welds are shown on Figures 7 and 8. One of the stainless steel repaired welds lasted about 11 million cycles at 11.6 ksi. The original weld had been a last-pass specimen that had failed at the toe at 10 million cycles under the same load. This time, the weld failed not at the new toe, but at the continuation of the original weld crack. Although the overlay did not arrest the original toe crack, it was still successful in restoring all of the fatigue life of the original weld. The second stainless specimen had originally been a Code standard weld that had failed at the root at 10 million cycles at 10.5 ksi. In this test, it was a runout at a stress of 11 ksi. The weld overlay was successful in arresting the original crack. The repaired weld was thus better than the original. In the carbon steel tests, both repaired welds were runouts. They had both originally been standard Code welds that had failed at the root after 7 million and 10 million cycles at 8 ksi. The repaired welds withstood 26 million cycles at 8 and 9 ksi respectively and did not show any evidence of crack initiation. It can be concluded from these tests that the weld overlay repair process was not only successful in restoring the original fatigue strength of the specimen, but it actually improved the weld's fatigue resistance. The weld overlay design used was more effective in arresting root cracks than toe cracks.

Fatigue Strength Reduction Factors

Fatigue strength reduction factors (FSRFs) were calculated as a means for quantifying the test results of the various socket weld designs. The FSRFs are approximate, as they are based on estimates of the endurance limit, a number of tests that were runouts, and a limited number of test points. Table 2 is a summary of the FSRFs for each of the categories of tests, based on the ratio of the endurance limit from the ASME Code mean failure curve to the apparent endurance limit from the testing results. Since the testing was terminated at approximately 2×10^7 cycles, the alternating stress corresponding to this number of cycles was taken as the endurance limit for the purposes of this calculation. For the 2" stainless steel specimens, the standard Code socket welds had an FSRF of approximately 3.4. The 2 x 1 leg size specimens improved upon this to a value of 2.3, versus 2.9 for the butt welded specimens. Similarly, for the carbon steel specimens, the standard weld FSRF was 3.5. The 2 x 1 welds reduced this value to 2.0, versus 2.4 for the butt welds. An apparent break in this trend is that, as observed previously in Reference 5, ¾" standard Code specimens showed less of an improvement in going to the 2 x 1 weld geometry.

This is due to the fact that the standard welds in this pipe size have a higher ratio of weld section modulus to pipe section modulus than in 2 " pipe and are consequently stronger. It appears that it is reasonable to use an FSRF of 3.9 for standard Code socket welds, and an FSRF of 2.6 for 2 x 1 leg size socket welds in vibration fatigue applications, independent of pipe size. This is consistent with the current ASME Section III Code requirement of $C_2K_2 = 3.9$ for standard socket welds and the lower bound of 2.6 for larger leg length welds. This applies only to welds with no root defects or lack of fusion. Testing of the samples with toe defects in this program resulted in an FSRF of about 5. The EPRI Handbook recommends a FSRF of 8.0 for “Poor” welds, which is intended to encompass welds with root or toe defects.

A comparison of the various weld treatments indicates that post-weld heat treatment had the most consistent benefit, with an FSRF of 2.5 for 2” stainless, 2.5 for carbon steel, and 2.6 for “last pass” welds had FSRFs of about 3, and the no-gap welds about 3.5.

The modification of the previously tested 1 x 1 welds, by building up the weld on the pipe side to a 2 x 1 profile, produced welds that were as good as or better than new 2 x 1 welds. For stainless steel, the FSRF for the built-up 2 x 1 welds was 2.2, versus 2.3 for new 2 x 1 welds and 3.4 for new 1 x 1 welds. For carbon steel, the FSRFs were 1.8 for the built-up 2 x 1, 2.0 for the new 2 x 1, and 3.5 for the Code standard welds. The weld overlay repairs were also successful in improving the fatigue strength of leaking, standard Code welds. The stainless steel welds that were repaired had an FSRF of 3.2, which is better than new standard welds, at 3.4. The results were even better in the carbon steel specimens, with an FSRF of 2.8 for the repaired welds versus 3.5 for new Code welds.

Table 2 - Fatigue Strength Reduction Factors

Category	**No. Tested**	**Avg. FSRF**
2” Stainless Steel Tests		
Code Standard (1 x 1)	2	3.4
2 x 1	5	2.3
1 x 1 Built-up to 2 x 1	2	2.2
Butt Weld	3	2.9
Weld Overlay Repair	2	3.2
PWHT	2	2.5
Last Pass	2	3.1
No Gap	2	3.7
Polished Toe	2	3.6
Smooth As-Welded Toe	2	2.8
Smooth Last Pass Toe	3	2.9
Poor Toe	2	4.8
2” Carbon Steel Tests		
Code Standard (1 x 1)	2	3.5
2 x 1	5	2.0
1 x 1 Built-up to 2 x 1	2	1.8
Butt Weld	2	2.4
Weld Overlay Repair	2	2.8
PWHT	1	2.5
No Gap	1	3.1
¾” Stainless Steel Tests		
Code Standard (1 x 1)	2	2.4
2 x 1	3	2.2
PWHT	1	2.6
Last Pass	2	2.3
No Gap	1	2.4

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the testing, it is concluded that socket welds with a 2 to 1 weld leg configuration (weld leg along the pipe side of the weld equal to twice the Code required weld leg dimension) offer a significant high cycle fatigue improvement over standard ASME Code socket welds. This weld design offers a superior improvement in fatigue resistance than does replacement of socket welded fittings with butt-welded fittings. Since vibration fatigue of socket welds has been a significant industry problem, it is recommended that this improved configuration be used for socket welds in vibration critical locations.

The majority of the test failures occurred due to cracks that initiated at weld roots. However, toe initiated failures occurred in tests at higher stress levels that were premature in comparison with identical tests in which root failures prevailed. Therefore, care must be taken with socket welds of any design to avoid metallurgical or geometric discontinuities at the toes of the welds (such as undercut or non-smooth transitions). Such discontinuities promote a tendency for toe failures which greatly reduces fatigue life. Tests of welds with intentionally poor toes clearly demonstrated the early failures that such discontinuities can produce. Polishing the toes did not provide any benefit, causing cracking originating at scratch marks. Because of the importance of the toe condition, the last pass improvement process (in which a final pass is added to the pipe side toe of a standard Code weld) cannot be given an unqualified recommendation at this time. The last pass improved specimens had a tendency to develop toe failures.

Other conclusions drawn from this program are that the code required axial gap in socket welds (1/16") appears to have little or no effect on high cycle vibration fatigue resistance (thermal expansion effects were not part of the test), and that post weld heat treatment appears to increase the fatigue resistance of standard Code specimens. Although post-weld heat treatment consistently showed improved results, it has the downside of potentially sensitizing austenitic welds for IGSCC in certain environments. Therefore, PWHT is not recommended for situations where IGSCC may be a damage mechanism.

The test data supports the use of the ASME Section III stress indices for standard Code welds (currently $C_2K_2 = 3.9$). It also indicates that this factor may be reduced to two-thirds that value (2.6) for 2 to 1 leg size welds. (The current Code lower bound of $C_2K_2 = 2.6$ is based on weld leg length, but it is a function of the shortest leg length.) Both of these values are appropriate only if the weld roots are free of defects such as lack of fusion or lack of penetration.

Testing of modification and repair concepts indicated that these approaches were successful in improving the strength of already installed socket welds without having to replace them with butt welds. Code standard 1x1 welds that were built up to a 2x1 profile performed as well as new 2x1 welds. Weld overlay repairs of leaking standard welds not only provided enough fatigue resistance for the welds to last to the next outage, but actually improved their fatigue strength to better than new standard Code welds. The weld overlay process was somewhat more successful repairing root failures than toe failures.

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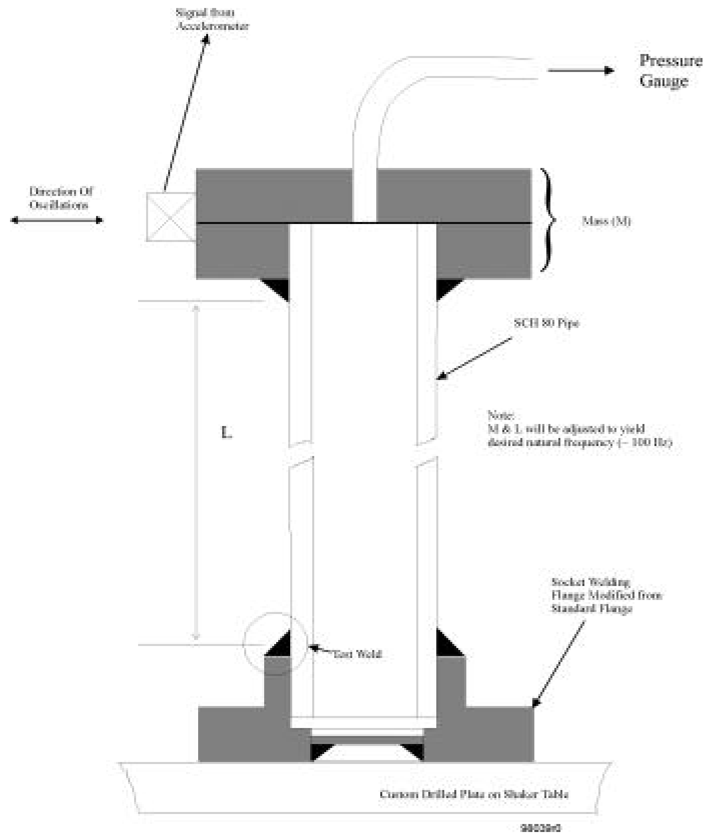

Figure 1. Test Setup

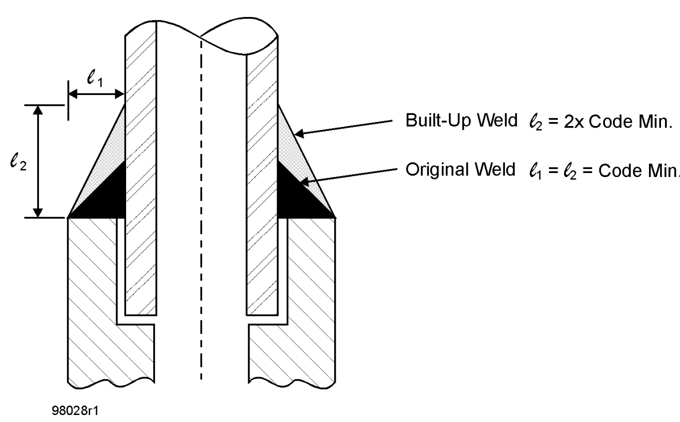

Figure 2. 1 x 1 Weld Built Up to 2 x 1

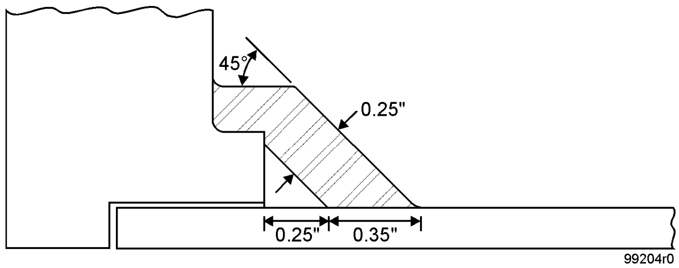

Figure 3. Weld Overlay Design

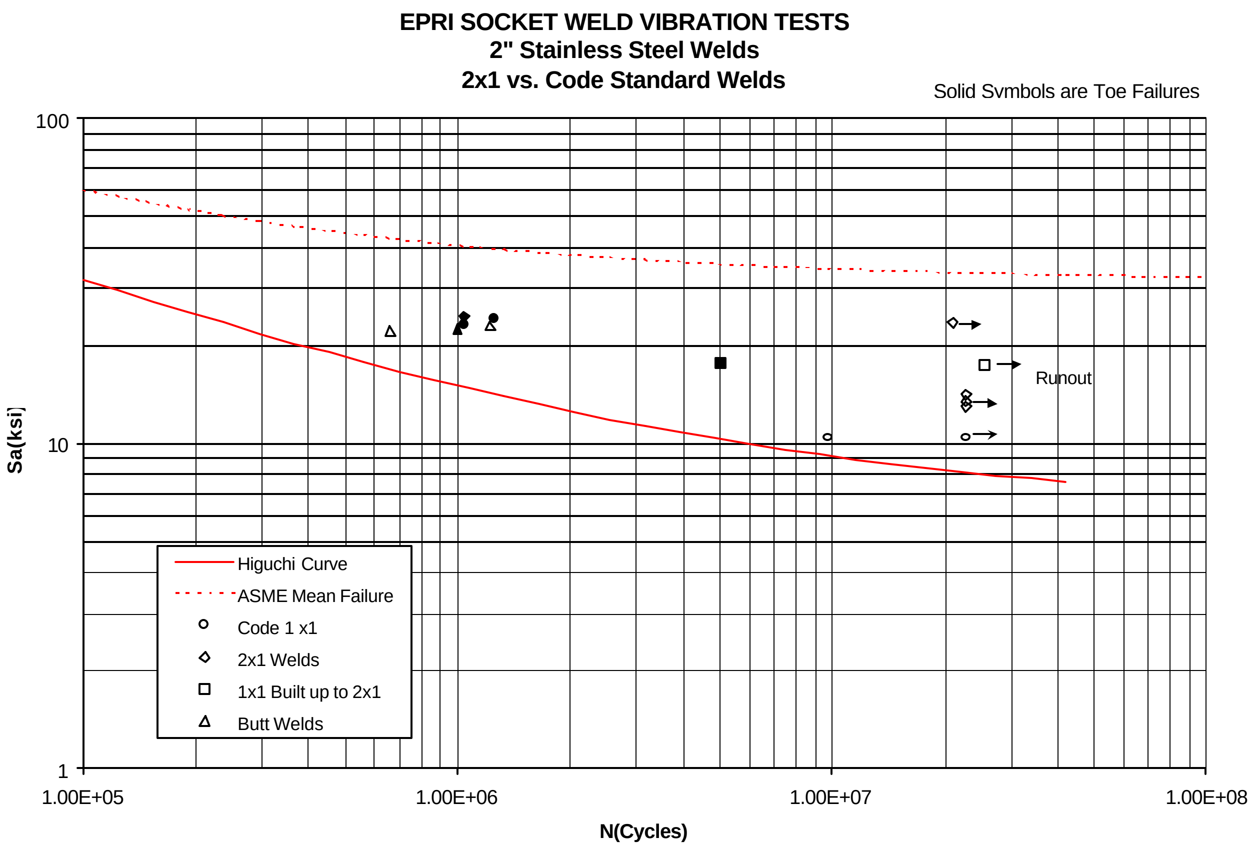

Figure 4. Weld Size, Stainless Steel

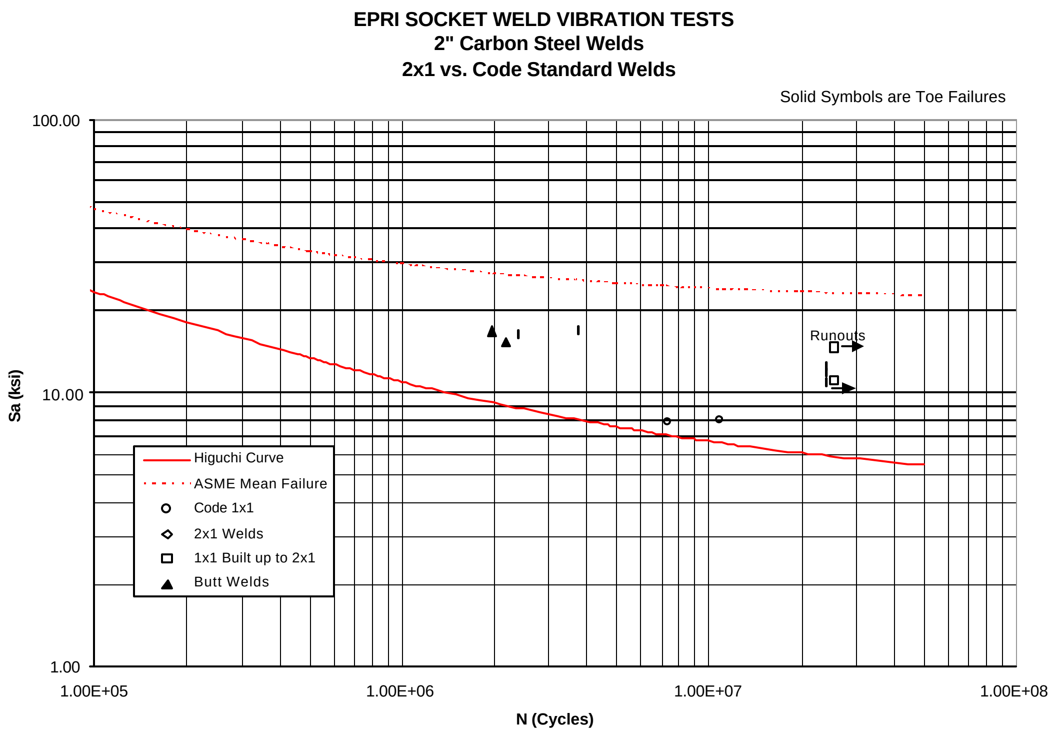

Figure 5. Weld Size, Carbon Steel

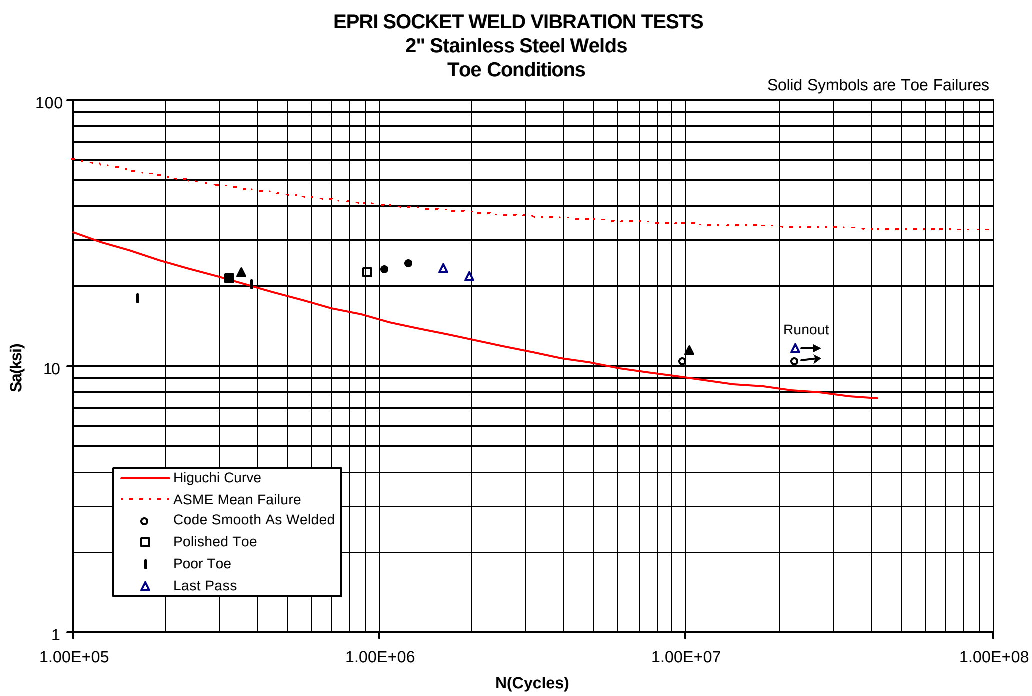

Figure 6. Toe Conditions

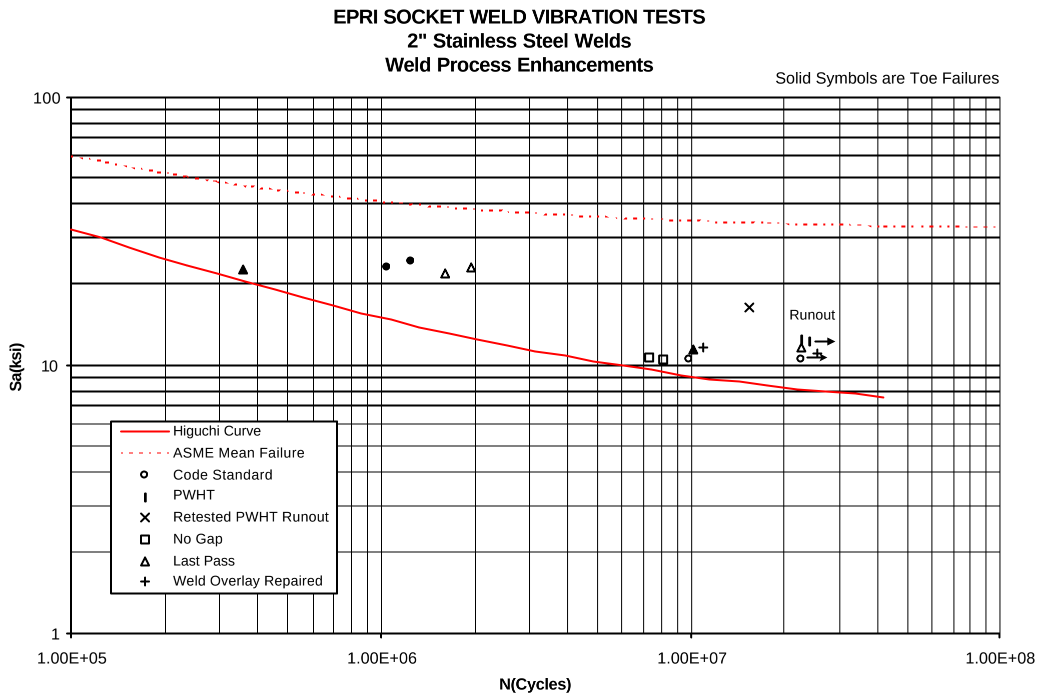

Figure 7. Weld Enhancements, Stainless Steel

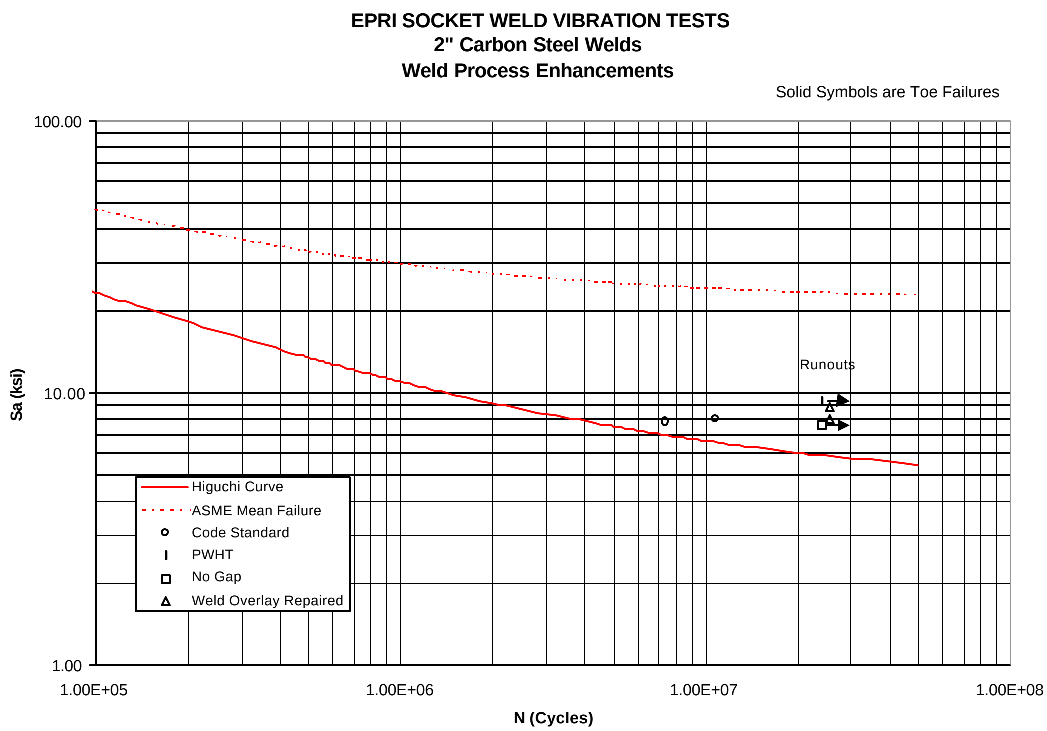

Figure 8. Weld Enhancements, Carbon Steel