THE EFFECT OF MICROSTRUCTURE AND GEOMETRY ON THE FATIGUE BEHAVIOUR OF BUNDLE ASSEMBLY WELDS

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ABSTRACT

Cracking of end plates, in the Darlington NGS, was attributed to high-cycle fatigue resulting from flow-induced vibrations. Because the cracks were predominantly associated with the bundle assembly welds and with certain element positions, a program was initiated to study whether the microstructure and geometry of the weld zone affected the fatigue behaviour of the assembly welds.

Assembly weld samples were subjected to different heat treatments, resulting in different microstructures of the weld zone. Results of fatigue testing suggest that heat treatment of the welds (i.e., microstructure) had little effect on the fatigue life. Assembly welds were also produced with different weld notch geometries, and compared with samples having notches produced by machining (instead of welding). The results of these tests showed that geometry of the weld had a significant effect on fatigue life. However, the geometry of the weld notch required to significantly improve fatigue life is not achievable using the current assembly welding process. A small improvement in fatigue life of welded samples appears possible by increasing the weld diameter.

1. INTRODUCTION

Fuel channel flow pulsations have been shown to cause fuel-bundle end-plate failures in the Darlington reactors [1]. The pulsations were eliminated by changing the impellers of the heat transport system pumps from 5-vanes to 7-vanes. As a result, a program sponsored by the CANDU Owners' Group (COG) was initiated to study the possible effects of microstructure and geometry on the assembly weld fatigue strength.

To study the effect of microstructure on bundle assembly welds, several identical samples were prepared; some were then heat-treated, to alter their microstructure. To study the effect of geometry, assembly welds were developed with different weld notch radii, by changing the weld preparation or the weld conditions. The assembly weld samples were subjected to fatigue testing and evaluated on the basis of number of cycles to failure. Figures 1 and 2 show typical test samples.

2. EXPERIMENTAL

2.1 Assembly Welds to Study Microstructure

Identical assembly weld samples were produced by welding a Zircaloy-4 strip to an end cap to simulate the end-plate-to-element-assembly weld. To test the assembly welds, the Zircaloy strip was held, and the end cap was pulled in tension-tension fatigue. Figure 3 shows a schematic of the gripping mechanism used for these tests.

2.2 Heat Treatment of Samples

The assembly weld samples were subdivided into different groups: some received no further treatment and were tested in the as-received and as-welded condition; some were post-weld stress-relieved, to determine the effect caused by a change in material strength; others were subjected to heat treatment that would alter the microstructure of the entire sample. The temperature for stress relief (400°C) was not sufficiently high to alter the microstructure, and therefore the as-welded and stress-relieved samples were treated as identical, from the viewpoint of microstructure. The range of heat treatments was chosen to give a difference in material properties and microstructures. The heat input (during welding) changes the microstructure of the Zircaloy, from cold-worked to recrystallized-alpha microstructure.

The identical assembly weld samples were subjected to the following heat treatments, under vacuum, to obtain the desired metallurgical condition:

As-Welded:	Samples were not heat-treated
Stress-Relieved:	400°C for 24 h, furnace-cooled
Recrystallized-Alpha:	800°C for 1 h, furnace-cooled
Transformed-Beta:	1000°C for 2 h, furnace-cooled

Metallographic examination of the cross-sections showed that the microstructure in the last two conditions had completely changed and that the weld heat-affected zones had been altered.

2.3 Fatigue Testing

Samples were fatigue-tested in tension-tension (under load control mode) at deflections, ranging from 0.03 to 0.15 mm at cycle frequencies of 5 or 10 Hz. Load control mode was selected for testing as it is more representative of the conditions experienced by fuel bundles in-service. Representative samples were tensile tested to evaluate the different material strengths (resulting from heat treatment) by pulling the end cap and sheath away from the test strip until the weld broke, or until the sample deformed sufficiently to release it from the grip. All tests were conducted at 310°C.

2.4 Prototype Welds to Study the Effects of Geometry

A constraint imposed on the development of these prototype welds was to retain an overall configuration compatible with current production fuel (element-to-end-plate position and spacing) and equipment (resistance welding processes). The welding characteristics of prototype assembly welds were established for a variety of different weld-preparation angles and different overall heat input using a single-phase resistance welder. Figure 4 shows a shadow profile of a typical bundle assembly weld sample.

2.5 Samples with a Machined Notch

To provide a measure of the maximum potential for improvement in the fatigue performance of assembly welds, "idealized" samples were machined from solid bar stock to simulate assembly welds having either a square or round end-plate-to-end-cap intersection (notch). The square notch was machined with a sharp cutting tool (Figure 5), and the round notch was machined with a tool having a 1 mm radius (Figure 6). These samples were designed to be free of weld-induced microstructural discontinuities, associated with the welded samples.

Some of these machined-notch samples were also heat-treated into the beta-transformation region (1000°C for 2 h and furnace-cooled), for comparison with results of the previous heat-treated welded samples.

3. RESULTS

3.1 Tensile Tests

Tensile testing of assembly welds confirmed that heat treatment of the samples reduced the strength of the assembly welds. Welds in the as-welded condition were typically strongest (average 2.8 kN), followed by the stress-relieved welds (average 2.5 kN), and welds with recrystallized-alpha microstructure (average 1.8 kN); and the welds that were heated into the beta-transformation range failed at the lowest load (1.3 kN).

3.2 Fatigue Tests on Heat-Treated Welds

The results of the fatigue tests are summarized graphically in the deflection versus number of cycles to failure curve (Figure 7). The results of all the tests, with different heat treatments, follow a similar trend. In most samples, the cracks appear to have typically initiated in the region near the weld notch.

As-Welded Samples: The number of cycles to failure on samples tested in the as-welded condition (no heat treatment) ranged from 90 000 to 1 000 000. Failure at 90 000 cycles occurred at a peak-to-peak amplitude of 0.090 to 0.100 mm. Failure at 1 million cycles occurred at an amplitude of 0.044 mm (peak to peak).

Stress-Relieved Samples: In samples that were stress-relieved, the number of cycles to failure ranged from 100 000 to just over 1 million. Again, failure time was dependent on the amplitude used. Failure at 100 000 cycles occurred at an amplitude 0.074 to 0.096 mm; failure at 1 million cycles occurred using an amplitude of 0.036 mm (peak to peak).

Alpha-Recrystallized Samples: Samples that were isothermally heat treated in the alpha-recrystallization temperature range, failed between 100 000 to 1 million cycles. Crack initiation typically occurred near the root of the weld notch.

Beta-Transformed Samples: Samples that were isothermally heat-treated in the beta-transformation range, exhibited a very coarse uniform (prior-beta) alpha microstructure, both in the weld area and the Zircaloy strip. Samples failed at over 100 000 cycles, at a deflection of 0.069 mm; 1 sample failed at over 1 million cycles, at a lower deflection of 0.039 mm. In these samples, failure occurred at the root of the notch and progressed through the coarse alpha microstructure (prior-beta grain boundaries).

3.3 Effect of Geometry on the Fatigue of Assembly Welds

The 4 types of prototype assembly welds tested (2 angles, 2 heats) suggest a small effect of welded geometry on fatigue life, as shown in Figure 8. Although there is some overlap, the following trends are apparent: welds having a low heat input failed at lower cycles than did those that had a higher heat input for both shallow and steep weld-prep angles. (Note that these welds also exhibited lower torque strengths to failure.) Note that these tests were conducted under identical load conditions, and the different deflection for each weld group indicates a different joint stiffness. Consistent with this observation, there appears to be a correlation between weld diameter and the number of cycles to failure (Figure 9); a larger weld diameter has the effect of increasing stiffness.

3.4 Fatigue Tests on Samples With a Machined Notch

The deflection versus cycles to failure for machined notch samples is shown graphically in Figure 10. The number of cycles to failure in these tests is significantly higher than in all previous tests, and the behaviour of the machined round notch is distinct from those with a machined square notch. In fact, at lower deflections (0.068 to 0.078 mm) the samples with the machined round notch did not fail, even after 2 000 000 cycles, indicating that these may be below the fatigue threshold limit. Conversely, samples with a machined square notch performed only slightly better than the welded samples of this study; that is, the number of cycles to failure was only slightly higher, for the same deflection. Note that with the machined round notch samples, higher loads (and hence a greater deflection) was required to achieve failure.

In these tests, there was little difference in the fatigue behavior of samples machined from the as-received bar stock and those subsequently heat treated to the Beta-transformation region.

4. DISCUSSION

4.1 Effect of Microstructure on Fatigue

These results indicate that heat treatment of assembly welds (beta or alpha microstructures) does not significantly affect their fatigue behaviour compared to the as-welded or stress-relieved samples.

The data plotted as Figure 7 suggests that, within the experimental scatter, these results fall roughly along a linear trend of deflection and cycles-to-failure. The results also indicate that there is a slight difference in the deflection (under similar loading) of as-welded and stress-relieved samples compared with the samples that were heat-treated to the alpha- and beta-transformation temperatures.

The results from the as-received and stress-relieved samples indicated that failure occurred in the notch region, which hosted the fine-grained recrystallized-alpha microstructure. Surprisingly, the number of cycles to failure was higher, although marginally, than for the alpha heat-treated samples. One might have expected that the combination of weaker microstructure and notch effect would have resulted in a decrease in the number of cycles to failure.

To refine or alter the microstructure in order to avoid recrystallized-alpha microstructures, the temperature of the weld pieces would need to stay below the recrystallization temperature during assembly welding. To accomplish this, the manufacturer would likely have to resort to a different welding technique, which would not be feasible or economical, considering the results obtained. As the results suggest that microstructure has little effect on fatigue life, assembly welds associated with large heat-affected zones (such as for producing dished end-plate profiles) should not be cause for concern.

4.2 Effect of Geometry on Fatigue

Within the range of conditions tested in this study, there appears to be a small effect of weld geometry on fatigue life, in the welded samples. Figure 8 shows that although there is some slight difference in the fatigue life of samples having a shallow versus a steep weld preparation angle (which resulted in a different weld notch) there is some overlap in the results. The results from the samples with machined geometry however, indicate that if the notch radius is large, then the effect is significant.

Fatigue tests on complete bundle assemblies indicate that end-plate design may be of greater importance in fatigue behaviour than the current tests suggest [2]. The stiffness of the bundle end plate, especially with respect to different element positions has been shown to result in preferential fatigue cracking, as in the Darlington end-plate failures [3]. This is considered to be outside the scope of this study. The correlation between weld diameter and fatigue life confirms that the stiffness of the weld joint has some effect on fatigue life.

As in this work, the above references observed that the fatigue cracks usually initiated in, and progressed through or near, regions of recrystallized-alpha grains. The implication is that metallurgical discontinuities may affect crack initiation and reduce fatigue life.

Comparing all tests in this study, it is concluded that only samples with a round notch (1 mm radius), machined from bar stock, have fatigue behaviour that is significantly better than the fatigue behaviour of the welded samples. At lower deflections, the samples with a machined round notch appear to fall below the fatigue threshold (Figure 11). Unfortunately, this type of geometry is not achievable with current welding processes.

There does not appear to be any improvement likely from heat treatment or re-design of the weld with the current production processes. However, an improvement in assembly weld fatigue life appears to be possible if a significant change in geometry can be effected using a different joining process.

5. CONCLUSIONS

The following conclusions are drawn from this study:

- Microstructure has little effect on the fatigue life of bundle assembly welds.
- Geometry of the weld notch has a significant effect on the fatigue life of welded samples. However, different joining processes may need to be considered if significant improvements in assembly welding are required in the future.
- With current fabrication processes, there appears to be only a small improvement in fatigue behaviour of assembly welds may be possible by increasing the weld diameter.

Although significant improvement of bundle assembly welding (such as enlarging the weld notch radius) is not readily feasible, the current bundle assembly welds are not expected to result in further end plate cracking, since the severe flow pulsations, which caused the cracking in the Darlington reactor, no longer exist.

REFERENCES

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3. M. Gabbani, T. Richards, A.M. Babayan, E.G. Price, "Mechanical Fatigue Simulation Testing of Fuel Bundles and Specimens for End Plate Failure", in CNS Proceedings of the 13th Annual Conference, Volume 2, Saint John, NB, June 7-10 1992.

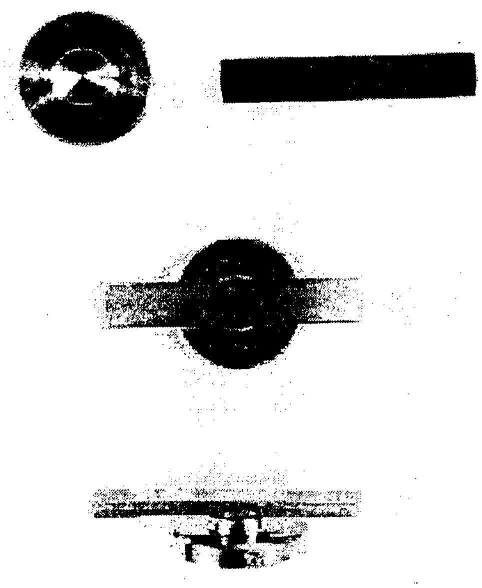

Figure 1.
End-Cap, Test Strip and Typical Assembly Weld Samples

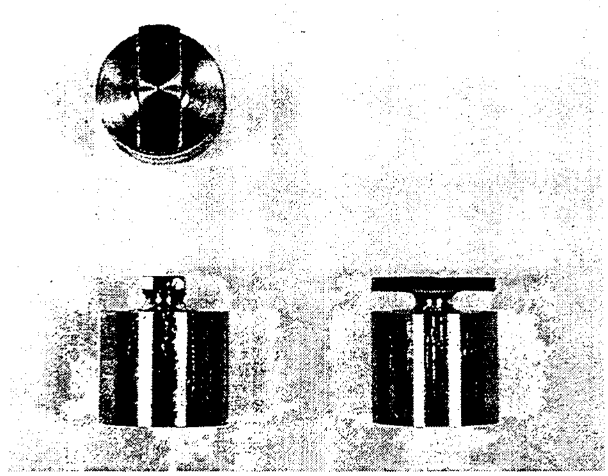

Figure 2.
Different Views of Machined Test Samples

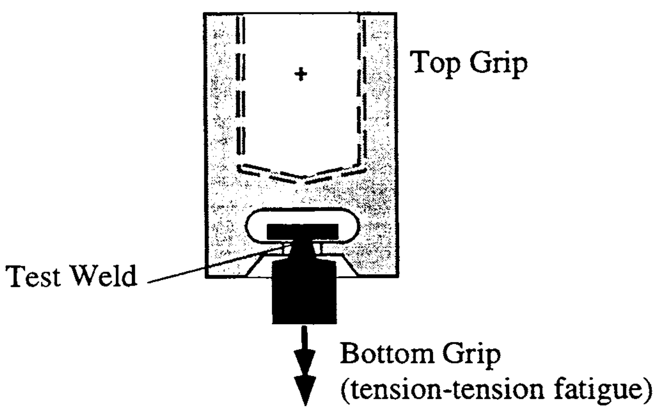

Figure 3. Schematic of Set-Up Used to Fatigue-Test Assembly Welds

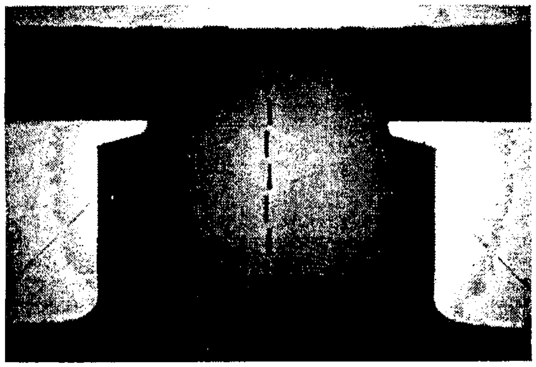

Figure 4. Shadow Profile of a Typical Welded Sample

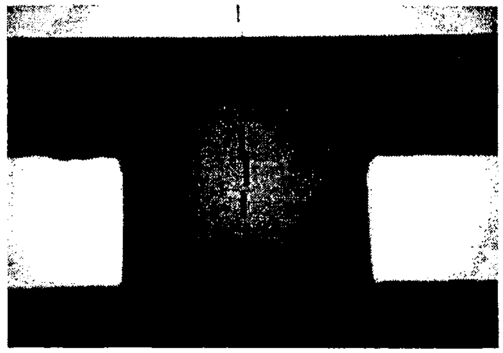

Figure 5. Shadow Profile of a Machined Square Notch Sample

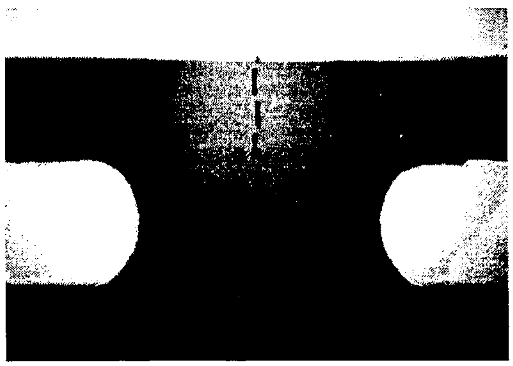

Figure 6. Shadow Profile of a Machined Round Notch Sample

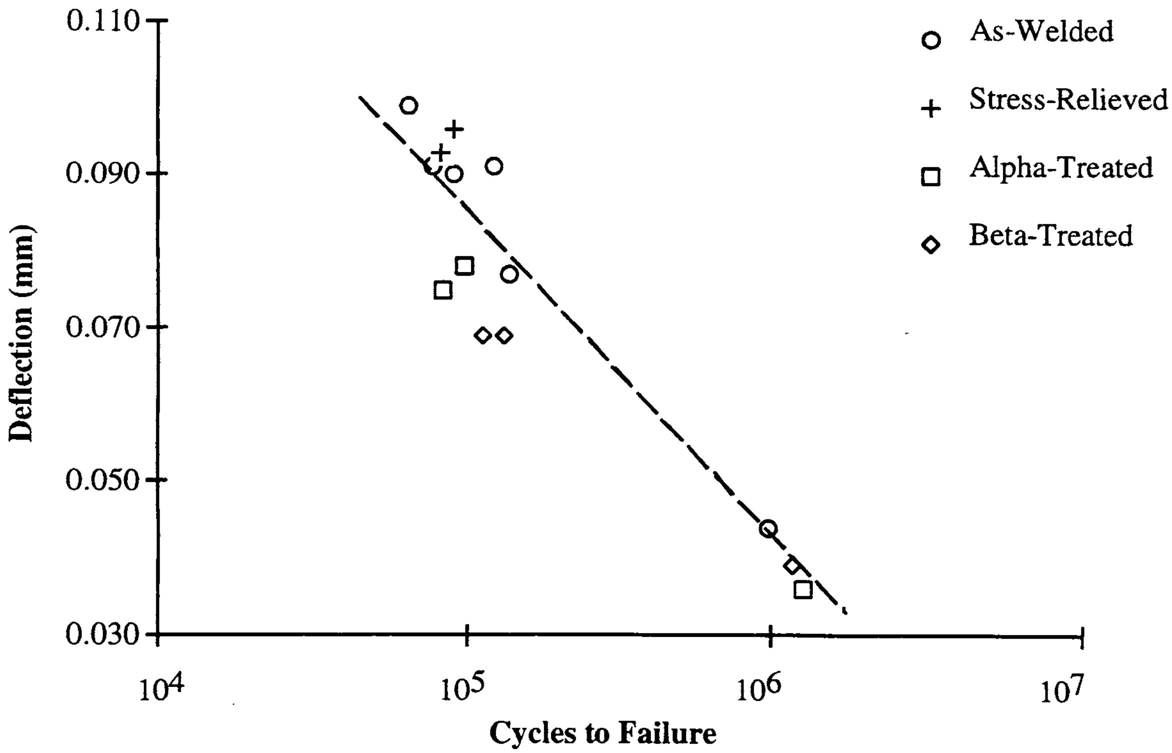

Figure 7. Deflection (Span) versus Cycles-to-Failure for Heat-Treated Assembly Welds

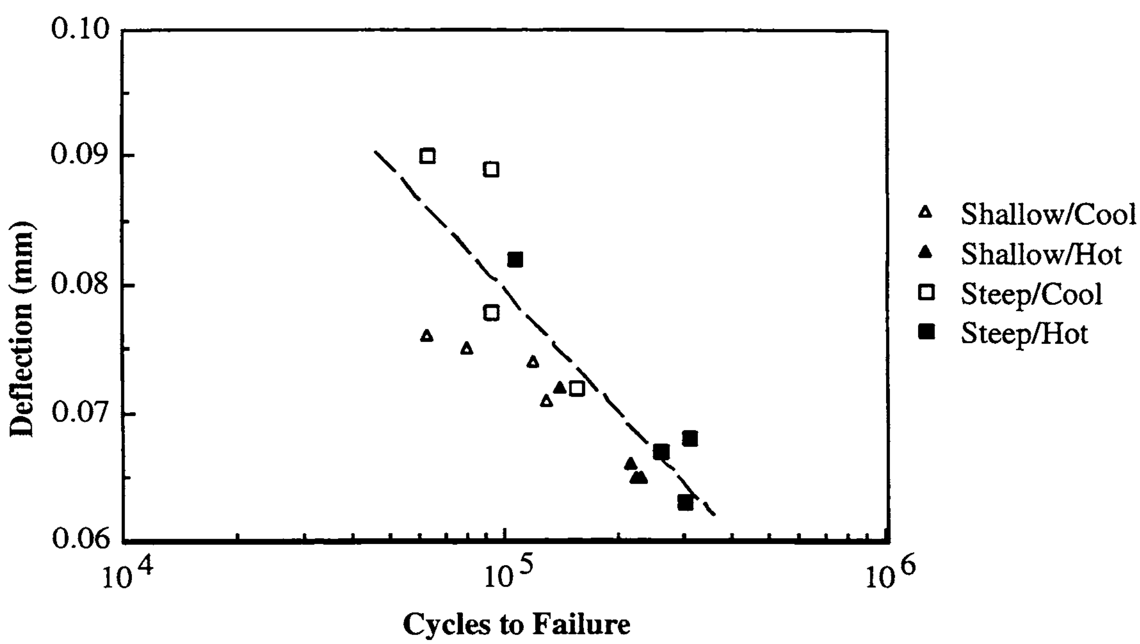

Figure 8. Deflection (Span) versus Number of Cycles to Failure for Prototype Welded Samples

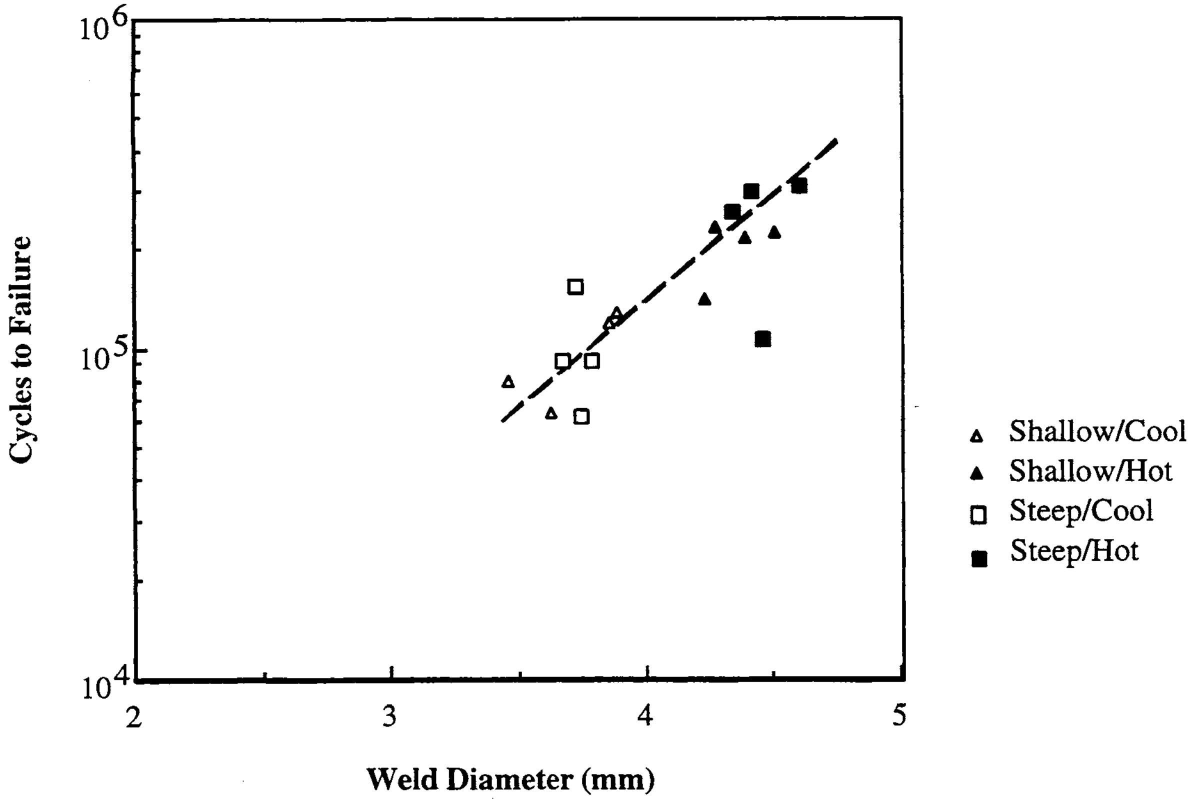

Figure 9. Cycles to Failure as a Function of Weld Diameter

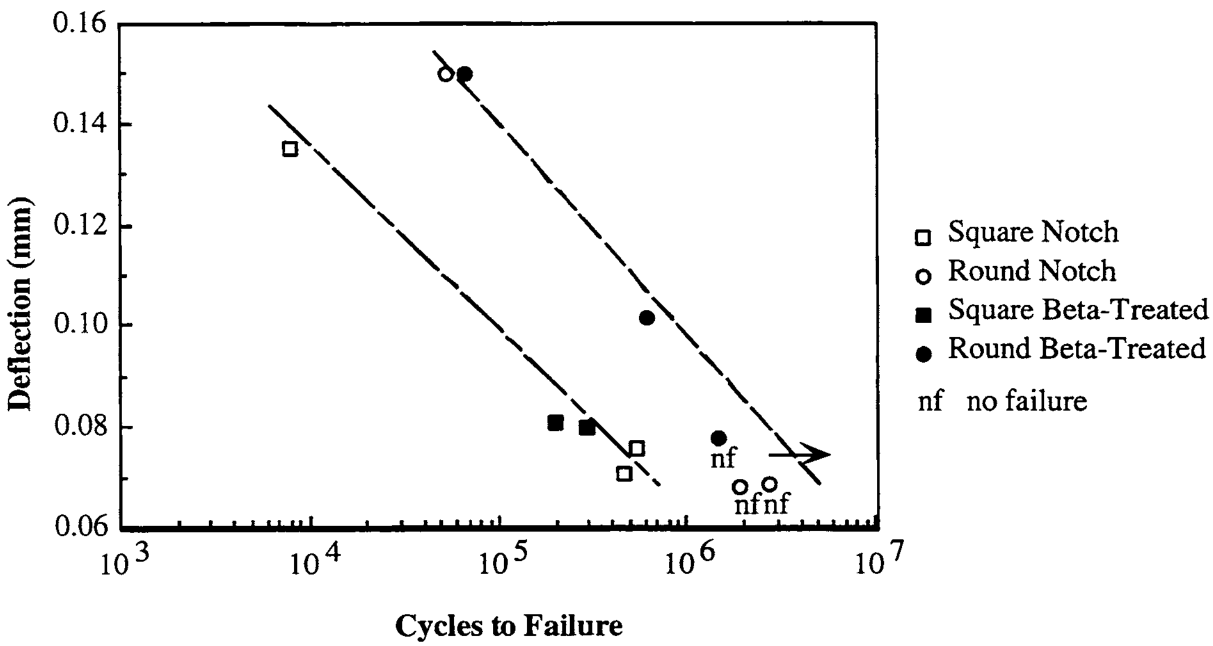

Figure 10. Deflection (Span) versus Number of Cycles to Failure for Machined Notch Samples (Including Heat-Treated Samples)

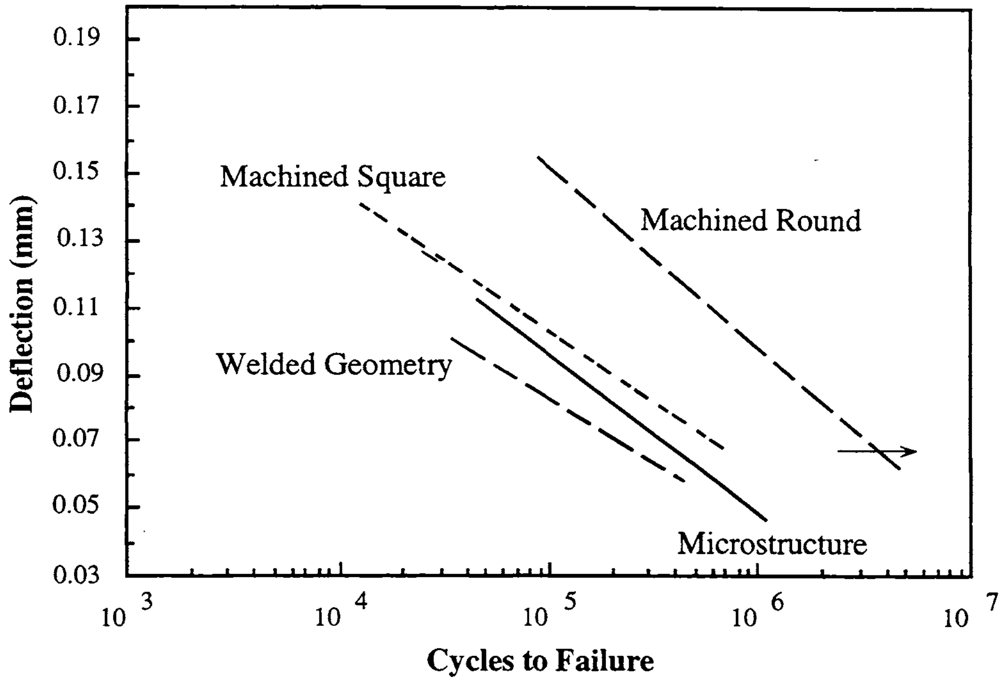

Figure 11. A Comparison of the Fatigue Life of All Samples Tested in this Study