# Assessment of Structural Integrity of Titanium Weldments for U.S. Navy Applications

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**Abstract:** The U.S. Navy has several uses for structural welded titanium, taking advantage of its good strength to weight ratio and corrosion resistance. Examples, both current and emerging, include M777 howitzer support components and aircraft elevator doors for aircraft carriers. As welding procedures are defined for these applications, weld strength and fatigue performance are structural properties crucial to the service capability. Acceptance criteria for weld imperfections can also be crucial to productivity and serviceability.

Data from these development programs will be shown and the larger context of knowledge on structural titanium weldments discussed, including effects of alloy content and welding process effects. Some of this context has been embodied in the first welding design code for titanium alloy welded structures D1.9:2007 from the American Welding Society, through its consensus standards process and the work of many volunteers.

Defining the provisions of this new code required collecting and summarizing both strength and fatigue data for titanium structural welds, including data from the howitzer welding development program. The design provisions were based on these data, but only in context of the other provisions of the code in areas of welding procedure qualification, fabrication, ballistic testing and inspection. For instance, the allowable imperfection sizes found on inspection had to be correlated with the expected fatigue performance of imperfect welds.

Some of the tension between individual application development and code provisions will be discussed, as well as their means of resolution. The accommodation for engineering computation and experience in this process will be described.

**Keywords:** titanium; welding; structure; fatigue; ballistic; strength

## 1. Introduction

The United States Navy applies titanium alloys in a wide variety of structures from aircraft to seawater piping on ships. This paper will focus on applications that are both structural and welded. Although this limits the cases, there is still a wide range of applicable areas from transportable weapon structures, as in the M777 howitzer for the Marines, to doors and sheet structures for ships.

Titanium's advantage over other structural metals is usually in its strength to weight ratio. It follows that applications which take advantage of this particular property, in transportable structures or materials or moving components, have the highest interest. The advantage of good corrosion resistance may also be built into a titanium alloy system by the choice of the particular alloy, such as resistance to general

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corrosion and pitting in seawater. Good elevated temperature strength may also be an important advantage, such as at exhaust ports.

## 2. AWS Structural Welding Code - Titanium

The American Welding Society (AWS) publishes standards, codes, and recommended practices in many areas of welding and joining. These include standards for welding consumables, guidance on welding for particular applications, examples of qualified welding procedures, and a set of structural welding codes. The Structural Welding Code – Steel (2008) can trace its history back to a first publication in 1928. Structural Welding Codes are also available for sheet steel, aluminum and stainless steel structures.

A new Structural Welding Code, which was published for the first time in 2007, is the Structural Welding Code – Titanium (2007), AWS D1.9:2007. This document covers design of the welded structure, qualification of the welding procedure, fabrication practices and inspection.

AWS has a routine process for the creation of a new standard. The standard is written in a committee of volunteer representatives of the industry and then reviewed in several steps to insure its value to the industry. Steve Luckowski of the U. S. Army Picatinny Arsenal has been the chair of the committee through the entire process of drafting the document. John Lawmon, of AEM, has been the vice-chairman. Volunteers from the fabrication industry, titanium manufacturers, end users and the research and development community were included on the committee.

The Structural Welding Code – Titanium was developed in the absence of a commonly used specification or an available design code for this set of alloys. Therefore, technical data was used by the drafters to justify the provisions.

The Code is unique among the AWS structural codes in giving guidance on welding structures for ballistic impact. These armor structures have special design, qualification, and testing requirements given in an annex to the document. These include a ballistic test plate design and testing method with acceptance and rejection criteria. This allows the code to be used more easily by contractors building structures that must withstand impact.

## 3. Weld Strength

Considerations of static strength of the welded areas of the structure must take into account that the primary way titanium welding consumables are specified is by grade. Unlike structural steel welding consumables, which are specified with a minimum ultimate strength, titanium welding consumables do not usually give an indication of the expected weld metal strength.

The choice of titanium welding consumable for a given alloy structure is usually limited to consumables that are the same grade or very similar to the grade of the base metal. Minor changes such as the addition of alloying elements for corrosion resistance or improved filler metal purity may be chosen. This suggests a system where the base metal properties are used to define the weld metal strength, except where dissimilar welds are specifically qualified.

The available test data during the creation of D1.9 indicated that the yield strength of butt welds in transverse tension might be slightly below the minimum yield strength for the base metal grade. The design strengths were given in the standard as 90% of the yield strength of the base metal grade. This approach may be conservative for commercially pure (CP) titanium grades, since the pick-up of impurities during welding can increase the strength of the weld metal above that of the base material.

This is unlike the approach for aluminum alloys where the weld metal is commonly dissimilar to the base metal and the weld area strength is significantly below the strength of the adjacent base metal alloys, so that each alloy system requires specific weld strengths for design.

An aspect of the issue with low strength of weld metal is that welder qualifications for welding Ti-6Al-4V or similar alloys may have the welder fail the qualification tests for weld tensile strength without having a recommendation for how to change the welding procedure to achieve a higher strength.

## 4. Weld Fatigue Performance

The fatigue performance of welded titanium structures was an area where additional testing was thought to be needed during the development of D1.9. The following sections discuss the available literature on fatigue performance, testing regarding effects of post-weld heat treatment, testing regarding weld configuration and imperfections and the comparison of test results for titanium alloys with differing strength levels.

### 4.1. LITERATURE SURVEY ON WELD FATIGUE

Several recent programs have examined the fatigue behavior of welded titanium alloys. In addition to the armaments industry, the offshore oil production industry has conducted testing on the fatigue performance of welded joints in titanium alloy compositions close to Ti-6Al-4V. While limited in scope and number of test results, the available results can be used to check the appropriateness of possible fatigue design curves for several configurations of welded joints.

Fatigue testing for the offshore industry has generally been directed to thicknesses near 20 mm and to butt welds with caps improved after welding. This focus on joints for risers has lead to studies of the internal locations, such as small pores, where fatigue cracks can initiate. Studies of this type have been reported by researchers from Conoco (Salama, 2000), the Norwegian University of Science and Technology (Berge, 1998a and 1998b), and by GKSS (Torster, 1999). Their results have shown a strong sensitivity of the fatigue performance to imperfections well below the detection limit of most nondestructive evaluation tools.

Grumman (Witt and Paul, 1975) tested a large number of butt welds, including butt welds with defects, in a test program in the early 1970s. The material was Ti-6Al-4V. Most of the tests were on 0.080- and 0.25-in. (2.0- and 6.4-mm) thick parts, although a few were on 1.5-in. (38.1-mm) thick parts. Fatigue testing was performed on 2-in. (51-mm) lengths of weld in transverse tension at R=0.1. Some very highly porous welds were obtained, making this an important reference for setting standards on acceptance criteria for porous welds. Several different welding processes (gas tungsten arc, electron beam, plasma arc, and gas metal arc) and several different procedures were used.

Some laser weld testing has been done, both as-welded and with reinforcement removed, as reported in Welsch (1994) and by Breinen and Banas (1975). Fatigue performance was improved by removal of reinforcement and undercut and by the shot peening used by Breinen and Banas.

Iwata (2001) reported tests on butt welds, transverse attachments and longitudinal attachments in thicknesses of 2 and 10 mm of commercially pure titanium (CP Ti). These results were compared against the steel classes in the International Institute of Welding (IIW) recommendation. Longitudinal attachments performed well below the steel design curves, while the other two geometries gave results close to the design curves for steel. These results are discussed further below.

The available fatigue test data for welds in $\alpha + \beta$ Ti alloys may be used to approximately define the design classes (FAT) that can be used for fatigue evaluation. The design FAT classes, as in the IIW recommendation (Hobbacher (1996)) for steel and aluminum welds, discussed here are shown in Figure 1.

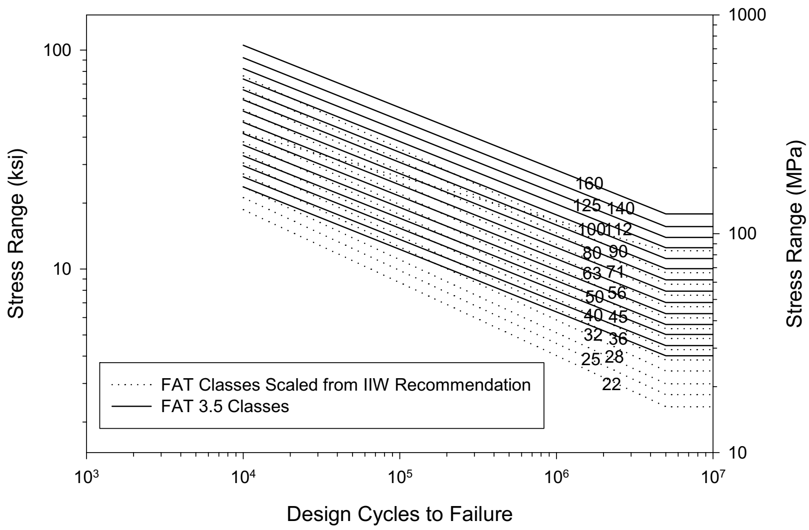


*Figure 1*. FAT and FAT3.5 class fatigue design curves.

The FAT class for butt welds in 0.16-in. (4-mm) sheet may be estimated as 56 to 71. Failures due to weld pores in butt welds in titanium can correspond to estimates of FAT class from 71 to 90. The FAT classes described in this section suggest that the design allowables for Ti-6Al-4V may be those described above as modified from steel or slightly larger. As discussed, the available literature S/N data can be compared directly to the FAT class curves and provide a range of FAT class results based upon weld geometry.

However, the slope of the reported S/N data is generally noticeably different from that assumed by the FAT class approach. The S/N curve slope of 3 in the FAT class approach is nearly always too small to fit the slope of any individual group of test data.

The collected data on fatigue crack growth rate for Ti-6Al-4V have a slightly different slope from that which best fits steel data. This difference in slope will also affect the S/N slope. For steels, the slope of the da/dN versus delta K data has been found to be just below 3 at 2.88 in studies for the basis of the British Standard BS7910. The slope found by Salama (2000) for Ti-6Al-4V was 3.2, noticeably larger than 3.0. Historically, the slope of the S/N curve has been slightly higher than the da/dN versus delta K curve. Thus, a slope slightly above 3.2 may be appropriate for Ti-6Al-4V.

The magnitude of the crack growth rates estimated by conversion from the steel design lines and those calculated by Salama are quite similar. The most prominent difference is in slope between that predicted from the steel data and that derived from tests on Ti-6Al-4V.

One way to improve the correlation between the S/N design lines and the test data would be to increase the slope exponent to 3.5 from 3. This would not exceed the description of slightly above 3.2.

New classes have been designated for AWS D1.9 called FAT3.5 Classes. These classes may be defined in the same way as the FAT classes, with the class number given as the stress range in megapascals at 2 million cycles and with an endurance limit at 5 million cycles. The FAT3.5 classes are shown in comparison to the FAT classes on Figure 1.

### 4.2. EFFECT OF POST-WELD HEAT TREATMENT ON FATIGUE

Post-weld heat treatment (PWHT) is widely used in fabrication of titanium components. It reduces the magnitude of residual stresses and stabilizes distortion produced by welding. Improvement of fatigue performance of welds due to PWHT has not been found in general. In steels, improvement is noted only when the loading is primarily compressive. Otherwise, no difference based on PWHT has usually been noted. In titanium alloys, fatigue performance may be modified by pick-up of oxygen in the furnace atmosphere by the titanium.

Fatigue tests on butt welds described were designed to distinguish effects of the type of PWHT history during tensile fatigue loading on Ti-6Al-4V alloy. Three sets of butt-welded specimens were prepared with differing heat treatments after welding and cutting. One set was not heat-treated (no PWHT). A second set was heat-treated in a vacuum furnace (vacuum PWHT). A third set was heat treated in air (air PWHT).

The 2.0-in. (50.8-mm) wide and 0.188-in. (4.78-mm) thick specimens were fatigue-tested in 4-point bending. Except for two variant specimens, all specimens were tested with a span between the outer rollers of 6 in. (152.4 mm) and a span between the inner rollers of 4 in. (101.6 mm), putting the weld cap in tension. The weld root was smooth on all three types of specimens, so the toe of the weld cap was the most important site of stress concentration on the specimen. One variant specimen was tested with different roller spans. The other variant specimen was tested with the root in tension and the cap in compression; this specimen cracked in the base metal.

Fatigue testing of the three heat treatments of butt-welded samples gave the cyclic lives shown in Fig. 2. The data is plotted in terms of calibrated stress range since the 4-point bend tests were not done with constant spans. The no PWHT specimens performed on average better in fatigue than the PWHT specimens, running about 50% longer under the same loading. No significant difference has been detected between the performance of air PWHT and vacuum PWHT. Since vacuum PWHT does not improve fatigue resistance compared to air PWHT, the extra expense of the vacuum furnace does not appear to be required.

### 4.3 EFFECT OF LOADING MODE AND WELD IMPERFECTIONS ON FATIGUE PERFORMANCE

Fatigue testing of several types of specimens was performed to provide greater understanding of the effects of welding imperfections and loading mode on the weld fatigue performance. Butt welds, corner joints and models of tang and slot welds in Ti-6Al-4V were used. The tang and slot welds were made into a T-shaped configuration with the welding heat applied on the opposite side of the crossbar from the T-stub attachment. The specimens were strips 2.0-in. (50.8-mm) wide and 0.188-in. (4.78-mm) thick. The tang and slot welds tested in cantilever bending were wider with a weld length of 2.17 in. (55 mm) using a moment arm of 1.56 in. (39.62 mm).

Several different welding procedures were used to induce welding imperfections into the welds including contaminating the shielding gas with air, detuning the welding parameters to provide linear defects and coating the filler wire with mineral oil to induce rounded pores. In 4-point bend loading of the weld details, the specimen was supported on four rollers, the inner pair at 4-in. (101.6-mm) apart and the outer pair at 6-in. (152.4-mm) apart. Cycles were applied in load control at R=0.1 to failure at full separation of the specimen.

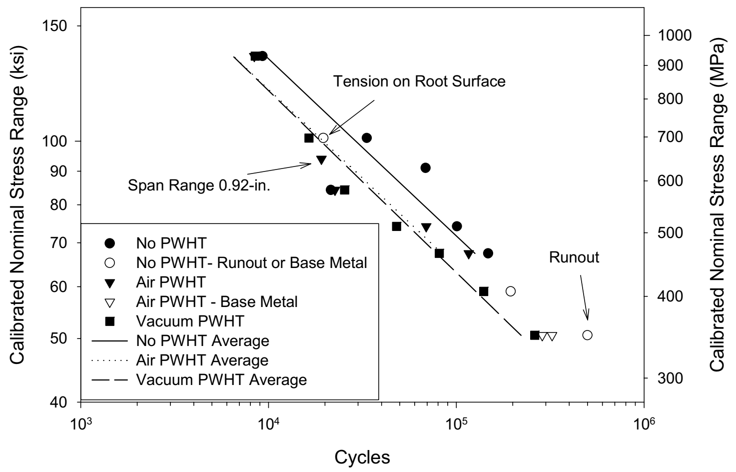


*Figure 2*. Fatigue performance of butt welds with differing PWHT in bending.

Butt joints of the air PWHT series described above were used as the baseline for butt joints in bending. These specimens were tested with the weld cap on the tension side of the bend and failed from the weld cap toe or from the base metal surface.

Figures 3, 4, and 5 show the bending fatigue test results for butt welds, corner welds, and tang and slot welds, respectively. The tang and slot welds were usually loaded in bending so that the crossbar of the T was stressed and the stub remained unloaded. One series was tested with the bending moment applied to the stub in cantilever bending. The stress range at the root of the weld is corrected by the calibration coefficients derived from the strain gage testing. Cases where the fatigue crack was in the base metal or where the test did not fail in fatigue, giving a runout, are noted on the plots.

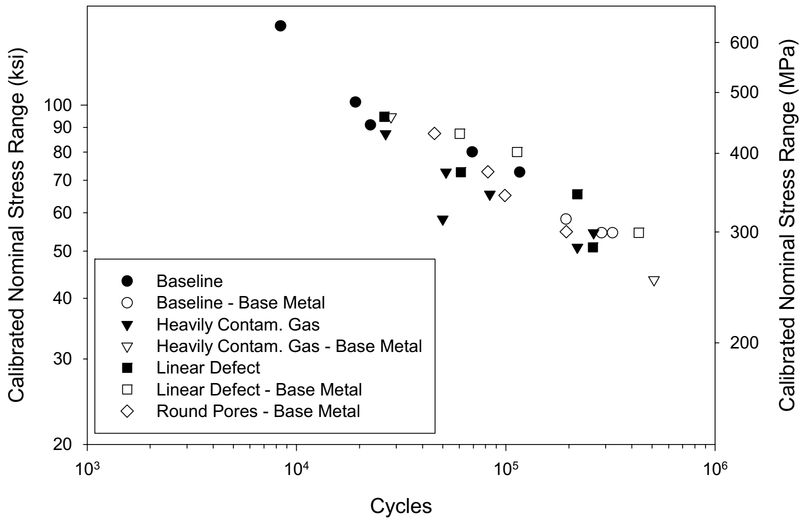


*Figure 3*. Fatigue performance of butt welds in four-point bending.

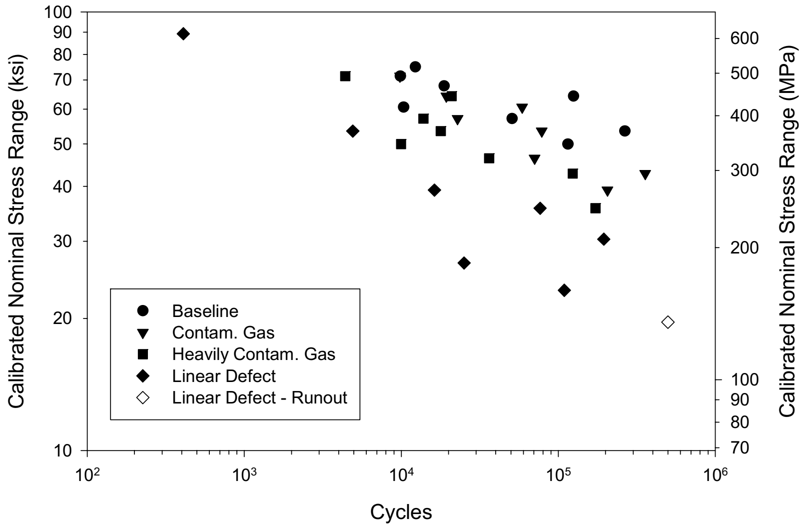


*Figure 4*. Fatigue performance of corner joints in 4-point bending.

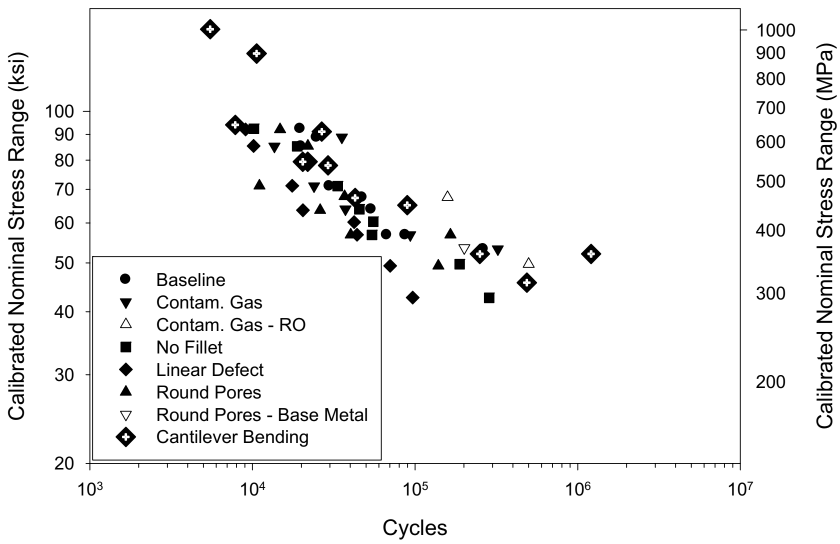


*Figure 5*. Fatigue performance of tang and slot model welds in bending.

Welding imperfections of three types were observed on the fracture surfaces under 10× magnification. These types were individual rounded pores, extended lack of fusion (LOF) imperfections, and unfused root corners. These welding imperfections were not observed on the tang and slot baseline welds or on the butt joint baseline (air PWHT) welds. Unfused root corners were observed on some specimens, particularly the linear defect specimens where procedures were adjusted to make this type of defect more likely. In these cases, the corner of the bevel on one side of the weld was not fused. The depth of the unfused area was measured based on the cutting striations from the root corner. Many specimens were observed to have more than one type of imperfection. For instance, all the butt-welded linear defect specimens that failed from unfused root corners also had extended LOF.

Figures 6, 7, and 8 show the tension fatigue test results for butt welds, corner welds, and tang and slot model welds, respectively. The lifetime results for tension loading were somewhat below those for bending loading. This is true even after the misalignment in the tension specimens is taken into account as part of the calibration procedure for butt joints and tang and slot joints. Thus, design curves that cover both bending and tension loading must be lowered from those that best fit the bending data to fit both classes of loading. The values for corner joints are nearly the same in tension and bending loading. In the corner joints the local stresses at the weld joint are overwhelmingly of bending type in the tension loading arrangement.

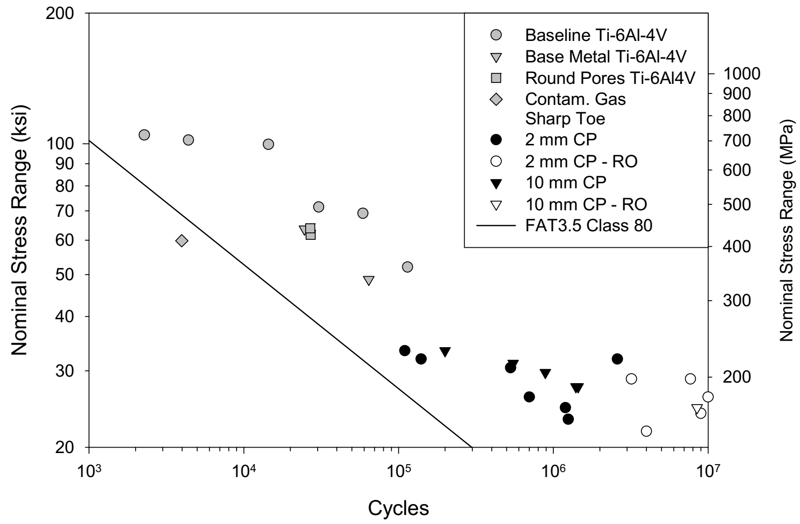


*Figure 6*. Fatigue performance of butt welds in tension.

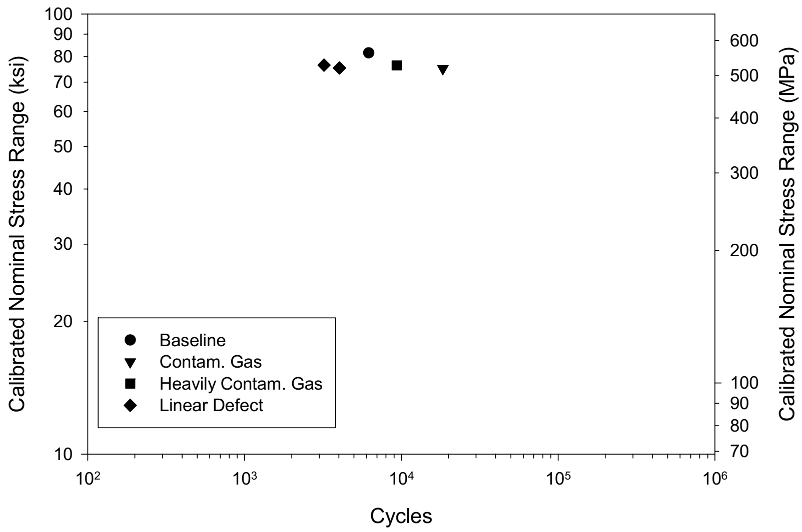


*Figure 7*. Fatigue performance of corner joints in remote tension.

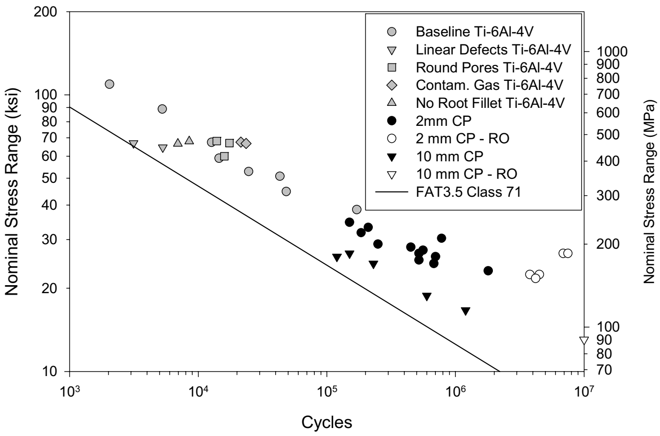


*Figure 8*. Fatigue performance of tang and slot welds in tension.

The heavily contaminated butt weld specimen had sharp toes on the weld root, one of which was the crack initiation area. Although this was not listed as a defect, it has the effect of reducing the fatigue performance. The contamination participated in creating these sharp corners by increasing the weld penetration when using the same welding parameters as for the baseline specimens.

The baseline results for the three joint types show the best performance for butt joints, followed by tang and slot joints, followed by the corner joints. The process variations from baseline all reduced the corner joint fatigue performance for lightly contaminated gas, heavily contaminated gas, and linear defect specimens. Much larger reductions were noted on the linear defect and heavily contaminated than on the lightly contaminated specimens. Much less effect of the procedure changes was observed on butt joints and tang and slot joints. The performance for the butt-welded specimen series with round pores was improved compared to the baseline.

The butt-welded specimen series with round pores was observed to fail in the base metal in all four bending tests. Each of these specimens was tested with the smooth and slightly concave weld root on the tension side of the bend. This surface geometry is conducive to the best fatigue performance, as shown in Figure 6, by redirection of the fatigue cracks into the base metal.

The linear defect series of corner joints exhibited all three types of weld imperfections, though not all on one specimen. The fatigue performance of the linear defect series of corner joints was best for those with unfused root corners and worst for those without unfused root corners. The reverse was true for butt joints. For butt joints, unfused root corners corresponded with lower fatigue performance and larger unfused root corners corresponded with poorer performance.

The extended LOF defects observed on corner joints appear to be correlated to lower fatigue performance within the best groups of the corner joints, the baseline, and lightly contaminated groups. The lower performing groups, heavily contaminated and linear defect, do not show a correlation of fatigue performance with the severity of LOF.

The presence and maximum size of pores was not observed to correlate with fatigue performance. Since the pores tended to be scattered along the weld length and in the center of the last weld pass near the cap, the pores were not found in the area of highest bending stress. This was observed for butt joints, corner joints, and tang and slot joints. The largest pore observed was 0.96 mm (0.038-in.) diameter. This size, 20% of the thickness of the sheet, is below the limit for individual pores established from the IIW recommendations. The scattered pores observed also did not approach the limit of 3% of weld projected area taken from the IIW recommendations. Thus, the experimental evidence of lack of effect of the observed pores on fatigue life corresponds to the expected lack of effect for these small pores.

Testing in tension did not greatly change the performance of corner joints, but did greatly change the performance of butt joints and tang and slot joints compared to 4-point bending. The tension test method for corner joints produced much more bending stress than tension stress at the weld root, since the weld joint is misaligned by several sheet thicknesses from the line between the gripping points. In fact, bending stresses exceeded tension stresses by nearly 30 times in the nominal stress calculation. So the differences in the loading for the corner joints were minimal between 4-point bending and tension testing.

Large differences in lifetime were observed for the butt joints and for the tang and slot joints between the tension and 4-point bending loading. The lifetime in tension was shorter by a factor of more than 4 from that in 4-point bending. The flaws found on the fracture surfaces of the tension test pieces were not, on the whole, worse than those on the bending test specimens. The flaws on the tang and slot without root specimens were larger than those tested in bending.

The large difference in lifetime between tension and bending could be partly due to misalignment across the weld inducing bending stresses. Centerline offset on some butt weld baseline specimens was more than 30% of the base metal thickness. However, the tension tests of butt joints and tang and slot joints from the mixed configuration specimens were observed to show no motion transverse to the sheet direction. Motion transverse to the sheet direction would be indicative of bending induced by misalignment.

### 4.4. COMPARISON AMONG TITANIUM ALLOYS

(Iwata 2001) has performed similar testing to that reported here in tension on welds in 0.08 and 0.39 in. (2- and 10-mm)-thick CP Ti. The data are shown in Figures 6 and 8 for butt welds and transverse attachments, respectively, and in Figure 9 for longitudinal attachments where the crack begins from the weld at the end of the attachment. Both the butt welds and the transverse attachments can be reasonably well described by extensions of the mean of the data from this program to lower stress ranges. The data for fatigue of longitudinal attachment ends provides information about a configuration that had been extrapolated from other materials to have better performance. A lower design line than the one marked on the figure was chosen.

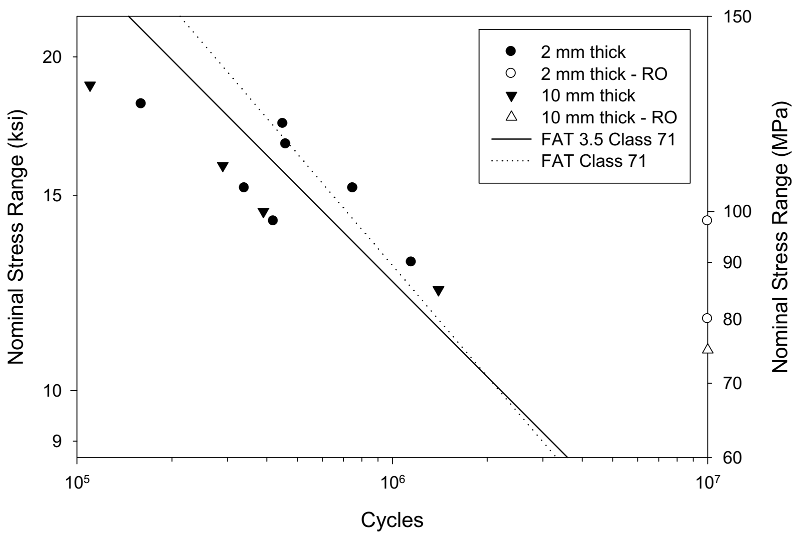


*Figure 9*. Fatigue performance of longitudinal attachment ends in CP Ti.

## 5. Example: Thin Section GMAW

Figure 10 shows the M777 howitzer in one implementation for the U.S. Marines, during a test with a stabilizer arm welded at EWI. Welded titanium alloy components have been used extensively as the design for this gun has evolved. The stabilizer arm had to meet both static loading and fatigue loading requirements.

The development of welding acceptance criteria for the howitzer program corresponded with the development of the AWS Code, so many of the tests for fatigue and static strength discussed above had the dual purpose of setting allowable imperfection sizes for the howitzer welds and providing baseline information for code development. The tang and slot welds were designed to allow external welding of internal stiffening bulkheads, for instance.

The association of the code development with the design work led to studies that could affect both, such as the utility of weld inserts that add solid metal to gas tungsten arc welds (GTAW) to limit welding distortion and control final weld bead shape. Another area of study was the effect of cast base metal on the structural performance.

*Figure 10*. M777 155-mm howitzer with many titanium components.

## 6. Example: Thin Section GMAW

Thin titanium sheet welding of Ti-6Al-4V, Ti-6Al-4V ELI and Ti 5111 has been demonstrated for applications using sheet thickness at and below 0.125 in. (3 mm). While small high-integrity parts are most effectively welded with GTAW, GMAW is more effective for larger area applications for shipboard use. GMAW is more efficient in using lower heat input for the amount of weld metal deposited, which can directly correlate to lower welding distortion in large area applications.

An example sheet titanium structural mock-up is shown in Figure 11. This mock-up demonstrates a full-length butt weld and fillet welds on the ribs and T-stiffeners. An important part of the challenge of this mock-up was providing sufficient shielding, including trailing shielding behind the torch using a new articulated device. Several procedures were tested, with a preference for pulse welding using 100% helium shielding gas.

The AWS code does not cover the smallest thickness parts welded on the mock-up, since it does not cover components with thicknesses below 0.125 in. (3 mm). This limitation on the small side was covered in this case by qualifying welding to more general Navy technical publication requirements under NAVSEA 248. The AWS code committee is considering the addition of provisions dealing with this thickness range. The strength and fatigue information in the D1.9 code should provide reasonable guidance on welded structure design for this case, although Iwata's data for the effect of thickness may indicate that the fatigue provisions may be somewhat conservative.

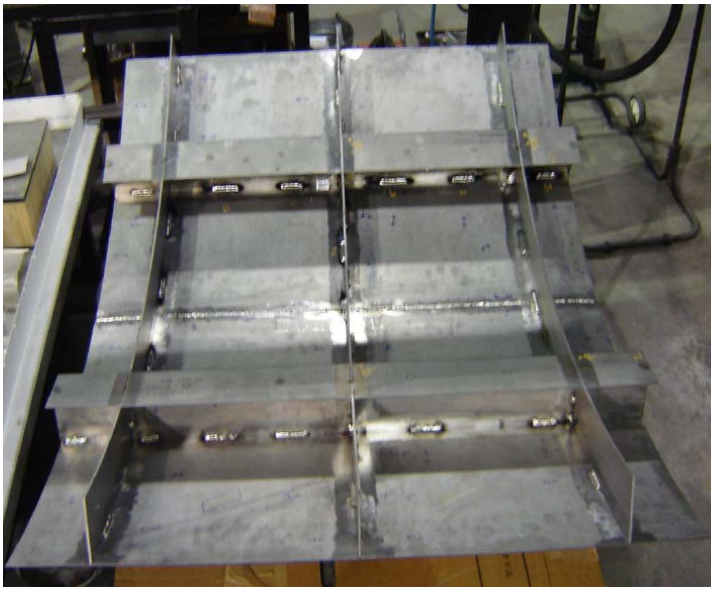

*Figure 11*. Mock-up structure in thin section titanium.

## 7. Example: Door Structure GMAW

Other shipboard applications demand greater thickness plate, but still benefit from the productivity advantages of GMAW over GTAW. An example is a sliding door for an aircraft carrier with internal horizontal and vertical stiffeners, which can be fabricated in strips and then butt welded together.

A mock-up for this design was made with 7/16 in. (11 mm) plate and 1/4 to 5/16 in. (6 to 8 mm) fillet welds as shown in Figure 12. The butt weld at the top represents the final weld of the outer panels, while the interior fillet welds model those joining the stiffeners to the outer plate and to each other. As in the thin sheet mock-up, the design of the shielding gas delivery is crucial to providing acceptable quality welds. The presence of spatter shown in Figure 13 for the inside overhead corner of the mock-up indicates that the welding procedures developed on individual weld segments must be reconsidered to make all areas of the weld with acceptable visual quality.

The strength and fatigue design guidance condensed in the AWS Code are directly relevant to the design assessment of the door structure. The one area where assessment must be focused is in the area of weld surface shape and tie-in to the adjacent base metal, since the presence of sharp transitions between the base metal and the weld was found to be important during the fatigue assessment. While the ballistic requirements given in the AWS Code are a valuable addition to its capabilities in the ground combat vehicle area, no use of these ballistic requirements can be considered for Navy shipboard applications. A completely different weld qualification for ballistic applications would be needed for the door weldment qualification.

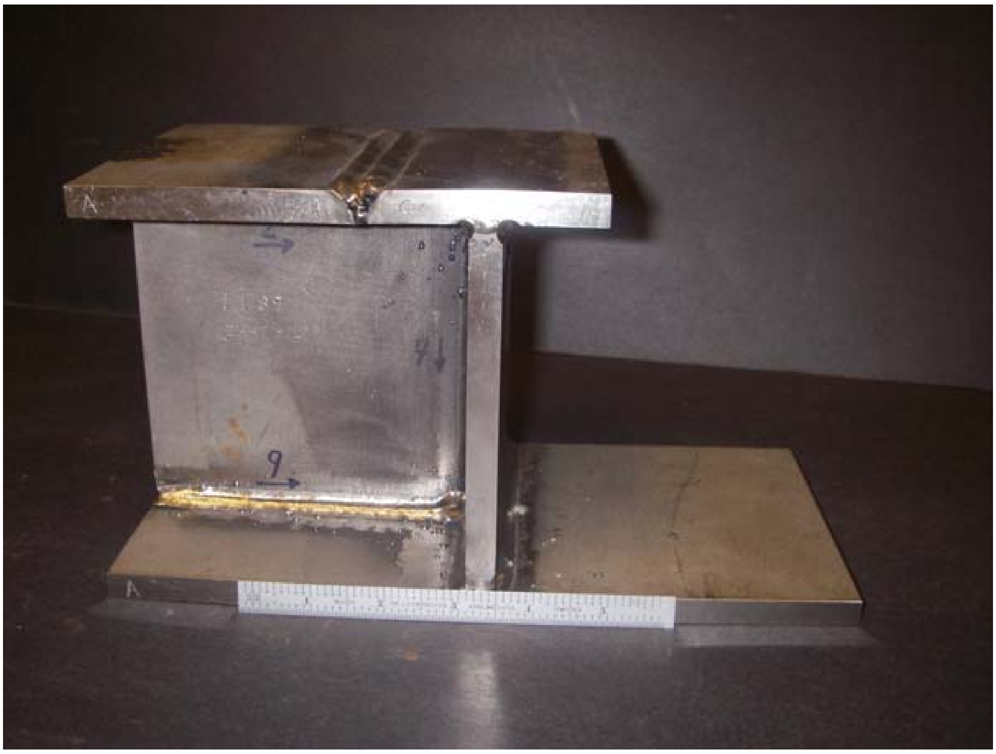

*Figure 12*. Mock-up of sliding door section.

*Figure 13*. Production of spatter in overhead corner area of overlapping filet welds.

## 8. Discussion

Several issues of transferability have been discussed above, including transferability of a requirement that welds have yield strength equal to the parent metal from steel to titanium, transferability of the slopes of the design curves for fatigue from steel and aluminum to titanium, transferability of fatigue results to other grades of titanium alloy, transferability of design guidance for thicker titanium to thinner titanium, and transferability of ballistic requirements for ground combat vehicle applications to shipboard applications. The acceptance of or the corrections to such a transfer must be demonstrated based on some data relevant to the new domain. Such situations may be easy to gloss over in preliminary engineering computation assessments of new types of structural design.

Judgment calls related to the transferability of data into a new setting are an important activity of code writing committees, such as the AWS Structural Welding Code committee and its subcommittees. These judgments must be made in the larger context of the rest of the code provisions, because each provision is used as part of the whole rather than on its own.

Working in the direction of defining general opportunities for engineering computation from the specifics of titanium structural weldments, suggests that there would be an advantage to defining stress for fatigue assessment in terms not only of direction of loading, but also in fraction of bending loading. The examples loaded in bending instead of tension gave lifetimes four times as long, but the resulting code section does not contain any provisions to take advantage of this because of the difficulty in specifying how the bending fraction should be determined.

## 9. Conclusions

Structural welded titanium has a variety of applications in the U. S. Navy's systems from shipboard doors to base components for a lightweight howitzer.

Structural welding need not place the structure in jeopardy of failure from hidden imperfections or those too small to be detected by conventional means. Design methods along with procedure qualification and acceptance criteria embedded in standards can be used to provide a structure that reliably meets its purpose.

Judgment calls regarding transferability or applicability of procedures and design data to generally accepted standards are helped by having a broad base of experts and expertise, such as that present for the volunteer AWS structural code committees and subcommittees.

Design methods that can define the degree of bending at welded joints for reference service loaded conditions may be able to use higher design capacities for fatigue performance.

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USMC Titanium Howitzer Welding Procedure Development, S2094 Gas Metal Arc Welding of Thin Titanium Structures for Navy Applications and S2021 Fabrication of Titanium Components for CVN 78.

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