Marine Structures 53 (2017) 1–19

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Fatigue of titanium weldments: S-N testing and analysis for data transferability among different joint types

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A R T I C L E I N F O

Article history:
Received 22 November 2016
Received in revised form 29 November 2016
Accepted 28 December 2016

Keywords:
Titanium weldments
Fatigue testing
Structural life prediction
Traction structural stress method
Finite element
TIG
MIG
Cruciform joints
Mesh-insensitive method
Stress concentration
Structural joints

A B S T R A C T

Fatigue testing of both TIG and MIG welded titanium components were first carried out using fillet welded cruciform specimens. A mesh-insensitive traction structural stress method is then introduced for establishing data transferability from one joint geometry to another and one base plate thickness to another. In addition, available test data from literature are also analyzed using the traction stress parameter proposed. Major findings are:

(a) There exist no noticeable differences in S-N curve behaviors between Ti-CP and Ti-6-4 weldments.

(b) The proposed traction stress parameter with a thickness correction term can be used to effectively correlate lab specimen test data in the form of a single S-N curve with a narrow scatter band regardless of joint types and base plate thicknesses, which has been demonstrated for both MIG and TIG welded specimens.

(c) By using both the S-N curve and traction stress parameter developed, satisfactory fatigue life estimates for a series of full-scale MIG-welded structural component fatigue tests have been achieved.

1. Introduction

Titanium and its alloys have been mostly used in aerospace industry due to their high strength to weight ratios and excellent resistance to corrosion environment [1]. For offshore structures, titanium and its alloys have been used for applications where lightweight, resistances to fatigue and corrosion are important, such as risers, as discussed by Baxter et al. [2]. To facilitate titanium riser design, Baxter et al. [2] proposed a fatigue design S-N curve which was referred to as RMI-Stolt design curve in 1997, with limited support data obtained using a set of fatigue tests of dog-bone shaped specimens with weld cap being ground flush. Subsequently, Salama et al. [3] proposed a design S-N curve by down-shifting smooth bar based S-N curve used by aerospace industry by one standard deviation to accommodate effects of "infrequently occurring defects" in Ti-6-4 (Grade 5, a designation according to ASTM) welded joints. He demonstrated the proposed design S-N curve was sufficiently conservative by carrying out fatigue tests using dog-bone shaped specimens in both air and seawater environment [3].

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http://dx.doi.org/10.1016/j.marstruc.2016.12.008
0951-8339/

More recently, Berge et al. [4] showed that both RMI-Stolt design S-N curve and the one proposed by Salama were not sufficiently conservative by comparing with their fatigue test results [5]. Thus, Berge et al. [4] suggested a more conservative design S-N curve, referred to as MARINTEK design curve. They [4] also carried out a series of fatigue tests for investigating the effects of titanium alloy grades (i.e., Grade 28 and Grade 29). They used hourglass-shape test specimens, extracted through water jet cutting process from a riser pipe section. The test results showed that the difference between the two grades of titanium alloys was rather small. They demonstrated that MARINETEK design curve was conservative for use in fatigue design of risers. This was further supported by dog-bone specimen test results on Grade 23 with specimens extracted from a welded pipe section [6]. In order to establish a basis for accessing significance of weld defects, Salama [7] reviewed available crack growth data on Ti-6-4 available at that time from about 20 laboratories including data from base metal and welded joints. As a result, two crack growth curves for offshore applications: one has an exponent of 3.75 using data processing procedure given in BSI PD 6493 (now referred to as BS 7910 [8]) and the other has an exponent of 3.2 based on linear regression analysis of test data.

In recent years, titanium has been shown to be increasingly attractive for ship hull applications for achieving lightweight and reducing total ownership cost, as discussed by Dong et al. [9]. However, unlike other hull materials such as structural steel and aluminum alloys, lack of comprehensive test data for supporting structural design is one major challenge for adopting titanium and its alloys for marine structure applications. It should be pointed out here that all test data described above for supporting riser design [2–6] were obtained using small dog-bone specimens in which weld cap and root are ground-smooth and therefore not directly applicable for ship hull structure applications. To address such a need, Iwata and Matsuoka [10] carried out a series of fatigue tests for weldments made of commercial pure titanium i.e. Grade 2 (denoted as Ti-CP hereafter), including transverse butt-welded plate, cruciform fillet-welded, and longitudinal gusset specimens. TIG welding process was used in manufacture of these specimens. The resulting test data were represented in the form of nominal stress range versus cycle to failure and were shown to follow three separate trend lines, each with significant scatter band. Their investigation suggests that a weld classification approach [11] could still be used for fatigue design of titanium structures, however, requiring a great deal of more test data from different joint geometries and loading conditions. To meet industry's needs, AWS recommended a series of design fatigue curves for titanium weldments referred to as “FAT Classes” in its D1.9 [12] with a S-N curve slope of 3.5 in log-log plot. In addition to the empirical nature of these FAT Classes in D1.9, joint types and loading conditions are rather limited for applications in complex structures.

In this study, we first start with an experimental investigation into fatigue behavior of titanium weldments made of Ti-CP (Grade 2) and Ti-6-4 (Grade 5) using cruciform specimens. Two types of welding processes are considered: Gas Tungsten Arc (TIG) and Metal Inert Gas (MIG) welding. To establish data transferability among different joint types and plate thicknesses, a mesh-insensitive traction stress parameter is then introduced. With this traction stress based parameter, both tests performed in this investigation and those available from literature are shown to follow a consistent trend line, demonstrating data transferability. Therefore, exhaustive testing can be avoided for developing design S-N curve for practical applications. Further validation of the present approach is then demonstrated by providing satisfactory fatigue life prediction of a number of full scale tests on MIG welded structural components [13,14].

2. Fatigue testing

2.1. Materials, specimen design and preparation

Both commercially pure titanium (Ti-CP) and titanium alloy (Ti-6-4) are considered here for fatigue testing as a follow up study to one reported by Dong et al. [9] on titanium ship hull structures. The mechanical properties as tested in this study are summarized in Table 1. The overall specimen dimensions are given in Fig. 1a, in which each individual specimen (of non-load-carrying fillet weld type) was extracted from a cruciform block containing a total seven specimens under the same welding conditions. Note that both base plate and attachment plate are of the same thicknesses in all specimens used in this study. Both TIG and MIG weld size definitions are illustrated in Fig. 1b and c, respectively. Note that the TIG weld size definition used here follows the definition given in AWS B4 [15] for treating concaved fillet weld profile. All specimen details are given in Table 2, with a total of 63 test specimens. The narrow strips on both sides of the welded blocks shown in Fig. 1a were used as weld macro specimens for examining fusion zone profile and fillet weld size. Representative macrographs showing fillet weld details are given in Fig. 2. Based on observations on weld macros (Fig. 2b), all TIG fillet weld profiles are defined as a quarter circle (i.e. a 90° arc) for consistently modeling and evaluating stress at weld toe. As such, the radius *R* can be related to weld

Table 1
Tensile properties of base materials.

Room Temperature Tensile Properties						
Materials	Orientation	Yield Strength		Ultimate Strength		Elongation
		Ksi	Mpa	Ksi	Mpa	
Ti-CP	Rolling	50	342	73	505	9.7%
Ti-CP	Rolling	126	869	149	1029	18.9%