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The Fatigue Behavior of Built-Up Welded Beams of Commercially Pure Titanium

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In this article, the results of a recent study aimed at evaluating, understanding, and rationalizing the extrinsic influence of fatigue loading on the response characteristics of built-up welded beams made from commercially pure titanium (Grade 2) are presented and discussed. The beams were made from welding plates and sheets of titanium using the pulsed gas metal arc welding technique to form a structural beam having an I-shaped cross section. The welds made for the test beams of the chosen metal were fillet welds using a matching titanium filler metal wire. The maximum and minimum load values at which the built-up beams were cyclically deformed were chosen to be within the range of 22-45% of the maximum predicted flexural static load. The beams were deformed in fatigue at a stress ratio of 0.1 and constant frequency of 5 Hz. The influence of the ratio of maximum load with respect to the ultimate failure load on fatigue performance, quantified in terms of fatigue life, was examined. The percentage of maximum load to ultimate load that resulted in run-out of one million cycles was established. The overall fracture behavior of the failed beam sample was characterized by scanning electron microscopy observations to establish the conjoint influence of load severity, intrinsic microstructural effects, and intrinsic fracture surface features in governing failure by fracture.

Keywords commercially pure titanium, cyclic fatigue life, GMAW-P welding, structural members, welded built-up beams

1. Introduction

Titanium has, since its emergence, grown in stature and concurrently in strength to be safely categorized as a modern metal that is viable for selection and use in high performance applications. It is much stronger and about half the weight of conventional structural steel and even the competing nickel-based alloys (Ref 1). A documented density of 4.5 g/cm^3 coupled with a combination of excellent corrosion resistance, wear resistance, ability to retain strength at elevated temperatures, and excellent mechanical properties are a few of the positive attributes that make titanium and its alloy counterparts an attractive candidate for selection and use in the aerospace sector. The earliest titanium alloys were developed in the United States during the early 1940s, and aided by sustained research and development, efforts through the years have resulted in the emergence of a few alloys. Of the few titanium alloys, the most popular and preferred choice was that of Ti-6Al-4V. The noticeably high strength-to-weight ratio [σ/ρ] and high stiffness-to-weight ratio [E/ρ], stemming from the high strength, high stiffness, and low density of the metal, have made titanium and is alloys an attractive candidate for airframe structural components and other performance-critical applications spanning both the defense and civilian sectors (Ref 1-5). An increasing array of armor structures, many precision components in the defense industry, and lightly loaded skins in aerospace applications are some of the examples, which have fostered the selection and use of commercially pure titanium (CP Ti Grade 2).

From the standpoint of cost, titanium and its alloys are expensive if one-to-one substitution of steel with titanium is desired. The continuing and urgent need to reduce costs while concurrently not compromising on the increased demand for maximization of component performance and minimization of component size has motivated manufacturers of end components to adopt a life-cycle approach toward material selection for the purpose of mechanical design. In more recent years, traditional researchers and the commercial industry have been making efforts to reduce the cost of titanium structures. A commercial approach that has been attempted most recently and put to effective use is the concept of built-up structures (Ref 6). Economic fabrication of built-up structural elements is made possible by the joining method called *p*ulsed *g*as *m*etal *a*rc *w*elding (henceforth referred to in this manuscript as the GMAW-P).

In a recently concluded research project (Ref 6) at the University of Akron, well-orchestrated research was systematically conducted with the specific objective of understanding the extrinsic influence of both static and fatigue loading on the response characteristics of built-up welded beams made from commercially pure titanium (Grade 2) and the titanium alloy

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(Ti-6Al-4V). An intrinsic aspect of this research project involved investigative studies on the fatigue performance of built-up beams. The results of this study on CP titanium (Grade 2) are reported and discussed in this article. The beams were made by welding titanium plates and sheets to form structural members having an I-shaped cross section such that the members could perform satisfactorily under conditions of fatigue loading thereby enabling to reduce the cost of structural elements that are either subjected to or experience fatigue loading during service. Specific details relevant to the fatigue tests performed on the Ti-6Al-4V built-up beams are outlined by the authors elsewhere (Ref 7).

2. Built-Up Welded Beams

A common type of structural member that is often used in the industry to support loads that act transverse to the longitudinal axis of the member is an I-shaped beam. The I-shaped beam provides the benefit of having a large ratio of moment of inertia (*I*) to total mass. Three plates can be put together or assembled, by welding to form the flanges and web of an I-shaped beam.

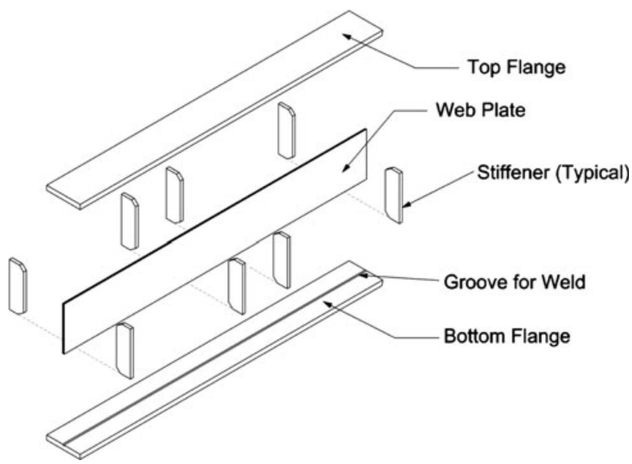

Fig. 1 The concept of built-up welded titanium beams

For structures made from commercially pure titanium or the alloy counterpart, it is a common practice to machine the required parts from either large castings or billets. Excess material is often removed from a thick plate or billet through the aid of precision machining, resulting in the wastage of substantial amounts of material. The resultant low material utilization contributes to the enhanced cost of the structural members that are directly machined from either castings or billets. Furthermore, thick section bars are far more expensive and difficult to make than the thinner counterparts, and require a longer lead time for procurement from material suppliers.

The concept of built-up beams from thin plate elements was introduced for titanium in an ongoing research project at the University of Akron (Ref 6). A schematic view of the built-up concept used in this study is shown in Fig. 1. An I-shaped cross section was formed by welding two flange plates (horizontal plates) onto a web plate (vertical plate). The loading points and locations at the two end supports are susceptible to local buckling. Consequently, they are provided with stiffeners with the objective of stabilizing the web at locations of the concentrated loads and resultant reactions. A typical cross section and elevation views of the welded built-up test beam are shown in Fig. 2.

The primary objective of the fatigue tests conducted in this study on the welded built-up beams made from CP titanium (Grade 2) was to investigate, rationalize, and understand the fatigue performance of such built-up beams under conditions of constant load amplitude cyclic loading. The authors believe that the demand for large structural welded built-up beams made from titanium and its alloys will increase over the next decade. The objective of this specific research study was to address the fatigue performance of the newly developed built-up welded beam concept using the GMAW-P process for manufacturing of large structural components made from titanium.

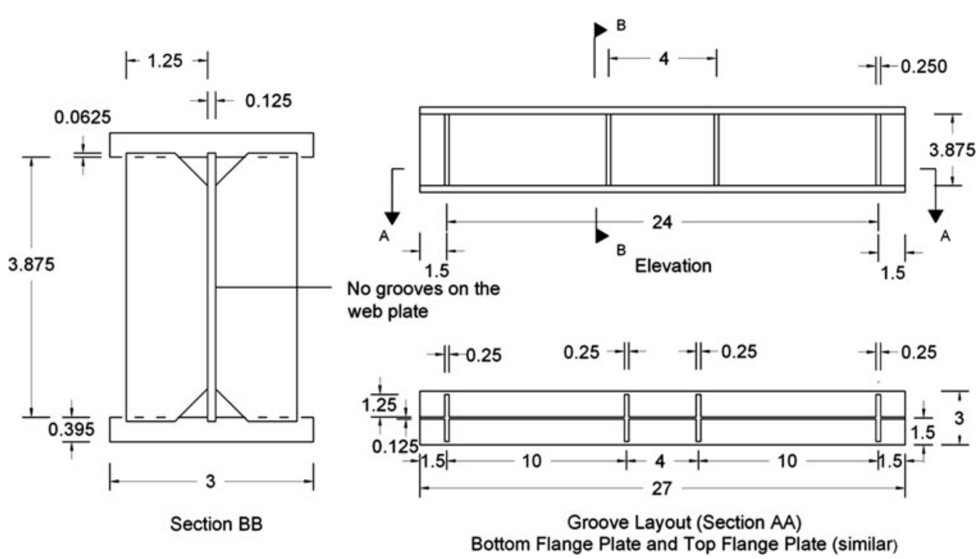

Fig. 2 Details of the built-up welded titanium test Beam B5 (test Beam B6 is similar, but with a total beam height of 4.79 in. and without grooves) [All dimensions are in inches (1 in. = 25.4 mm)]

3. The GMAW-P Welding Technique for the Fabrication of the Test Beams

The US Army's division at Picatinny Arsenal (NJ) developed a *p*ulsed *g*as *m*etal *a*rc *w*elding process (GMAW-P), which involved a suitable modification of the existing welding practices so as to be readily applicable to titanium and its alloys (Ref 8-10). Most noticeably, the linear weld speeds can be raised to be ten times faster than the corresponding speeds for tungsten inert gas (TIG) or gas tungsten arc welding (GTAW) processes and reduced number of passes (one-third of the TIG and GTAW processes). This process uses 100% helium gas shielding to facilitate good penetration capability. The welding of titanium is standardized in a recently released welding specification put forth by the American Welding Society (AWS) [AWS D1.9/D1.9M; Ref 11]. With the development of this welding process, it is certainly much easier to make welded built-up beams using titanium plates as shown in Fig. 1 and 2. The intrinsic details relevant to the welding process used in this study are provided by the authors elsewhere (Ref 12).

4. Fabrication of Test Beams

All of the required parts shown in Fig. 1 for the test beams were precision cut using water-jet cutting. The required grooves for welding were made by CNC machining. The grooves were specified as part of the GMAW-P welding protocol. The test beams were prepared for welding, after the individual parts were ready for fabrication. The tack-welded test beam is shown in Fig. 3(a). The fully welded test beams that were used for the fatigue tests are as shown in Fig. 3(b). All of the welds made for the test beams were fillet welds. The matching titanium filler metal wire diameter was 0.045 in. (1.14 mm). The welds were visually inspected and were found to be sound. However, the welds were not stress relieved subsequent to the welding operation. The intrinsic details relevant to the welding process parameters can be found elsewhere (Ref 6).

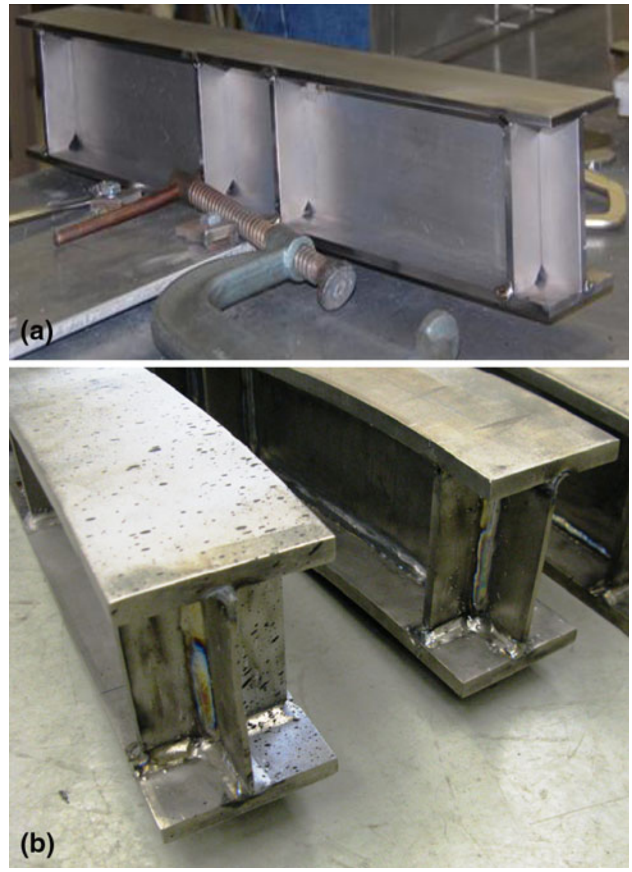

Fig. 3 (a) A typical tack-welded titanium test beam. (b) Fully welded test beams of CP titanium (Grade 2)

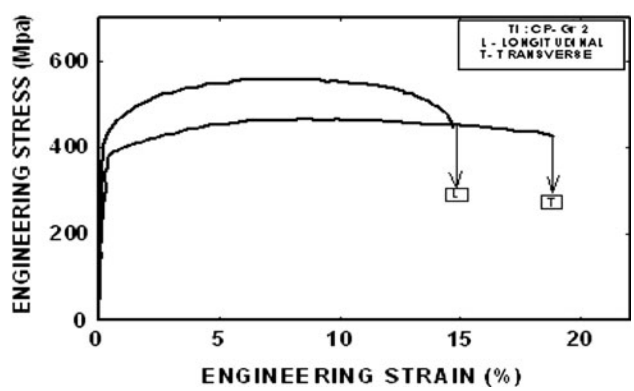

Fig. 4 The engineering stress vs. engineering strain curves for commercially pure titanium (Grade 2) in both the longitudinal and transverse orientations

5. Materials

Commercially pure titanium (Grade 2) plates were used for welding and manufacturing of the built-up structural test beam specimens. These plates were provided by TICO Titanium (Wixom, MI) in thicknesses of (a) 3/8 in. (9.5 mm), and (b) 1/8 in. (3.2 mm). The plates conformed to specifications outlined in ASTM Specification B-265-06/ASME SB-265-A06 GR. 2 EN 10024:2004 Type 3.1. The average specified tensile strength was 70.25 ksi (485 MPa) for the 1/8 in. (3.175 mm)-thick plates, and 73.5 ksi (506.8 MPa) for the 3/8 in. (9.525 mm)-thick plates. The specified yield strength based on 0.2% offset strain was 49.5 ksi (341.3) and 52.1 ksi (360 MPa), respectively, while the minimum specified elongation was between 26 and 33%.

Uniaxial tensile tests were performed on a fully automated, closed-loop servo-hydraulic mechanical test machine [INSTRON-8500 Plus] using a 100 kN load cell. The tests were conducted at room temperature (300 K) and in the laboratory air (Relative Humidity of 55%) environment. The test specimens were deformed at a constant strain rate of 0.0001/s. An axial 12.5 mm gage length clip-on type extensometer was attached to the test specimen at the gage section using rubber bands. The stress and strain measurements, parallel to the load line, and the resultant mechanical properties, such as, stiffness, strength (yield strength and ultimate tensile strength), failure stress, and ductility (strain-to-failure) were provided as a computer output by the control unit of the test machine. A typical stress versus strain curve obtained from tensile tests performed on CP titanium (Grade 2) is shown in Fig. 4. A summary of tensile test results is provided in Table 1.

Table 1 Room temperature tensile properties of commercially pure (Grade 2) titanium plates

Material	Orientation	Elastic modulus		Yield strength		UTS		Elongation GL = 0.5″, %	Reduction in area, %	Tensile ductility $\ln(A_o/A_f)$, %
		msi	GPa	ksi	MPa	ksi	MPa			
Commercially pure (Grade 2)	Longitudinal	16	115	63	432	81	561	14.7	43.4	57.0
	Transverse	15	108	55	382	67	465	18.9	47.0	63.0

Results are mean values based on duplicate tensile tests

The observed noticeable difference in the engineering stress versus engineering strain response of the two orientations is ascribed to intrinsic microstructural contributions. The intrinsic features playing a key role are grain size, grain boundary area, and grain boundaries. The marginally larger grain size along the transverse orientation of the welded plate of CP Ti (Grade 2) when compared with the longitudinal orientation is responsible for the observed lower strength and concomitant enhanced ductility, quantified by strain-to-failure, along this orientation.

6. Mechanical Beam Testing

Two welded commercially pure (Grade 2) titanium built-up test beams were fabricated for the fatigue tests.

6.1 Test Setup and Instrumentation

The two welded built-up test beams that were tested in fatigue were identical in length having a total length of 27 in. (662 mm), and a span between the simple supports placed at either ends to be of 24 in. (610 mm). The two central loading points were 4 in. (102 mm) apart. The test beams were loaded in fatigue using an MTS loading frame having a maximum capacity of 50 kips (222.4 kN) and a 10 in. (254 mm) stroke. A standard four-point bend test setup was used for the fatigue tests. Details of the test setup are shown in Fig. 5. The reaction beam fixture was commercially procured fixture that is used for the purpose of conducting standard four-point bend tests and fatigue tests. The specimens were supported on two rollers that allowed the ends of the beam to behave in a simply supported condition. The load was applied through a loading fixture that was attached to the load cell of the MTS test frame at the top. The loading fixture, i.e., spreader beam, was specifically fabricated for this project. The two central loading points of the spreader beam were 4 in. (102 mm) apart to match with the two stiffener locations. It is a common practice for beam tests of this nature to provide bearing plates under the loading points and above the support points to spread the load over a larger area (length) of the test beam. However, no such bearing plates made of steel were provided in the tests primarily because such loose plates in the test setup would tend to move away from the loading (or support) fixtures during fatigue loading thereby causing inaccuracies to occur. It was not necessary to monitor strains during the fatigue tests, and hence strain gages were not attached to the test specimen for the purpose of recording strains. The mid-span deflection was constantly measured over the entire duration of the fatigue test using a LVDT (Linear Variable Differential Transducer). The LVDT transmitted electronic data to the MTS controller during the sequence of fatigue loading. The data pertaining to load and central deflection were periodically collected by the MTS controller.

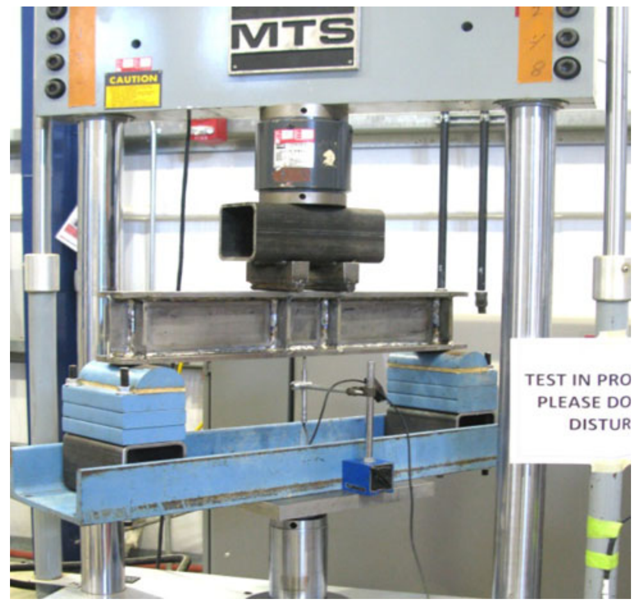

Fig. 5 The test set-up for the fatigue tests

6.2 Test Procedure

The theoretical failure load of the beams was calculated using the design equations reported by the authors elsewhere (Ref 6). The predicted loads were used for determining the range of loading of the test beams under conditions of fatigue loading. The failure load was predicted to be

(i) 36 kips (160 kN) for Beam B5 of CP titanium (Grade 2),
(ii) 38 kips (169 kN) for Beam B6 of CP titanium (Grade 2).

It is to be noted that the predicted theoretical failure load for the two test beams is marginally different because the overall height of the cross section of Beam B6 (4.79″ or 121.7 mm) is slightly greater than that of Beam B5 (4.66″ or 118.5 mm). A minimum load of 0.5 kip (2.22 kN) was initially applied to each test beam during the fatigue tests so as to ensure firm contact between the beam and the loading points or the supports. The load was applied in a sinusoidal wave form at a constant frequency of 5 Hz.

Table 2 Maximum and minimum loads applied to the test specimens for fatigue tests

	Predicted failure load (kips), P_u	Load (P)		P_{max}/P_u, %	Load cycles (N_f)
		Max., kips	Min., kips		
CP Grade 2 Ti Beam B5					
Stage 1	36	20	2.0	55.5	35,364
Stage 2		8	0.8	22.2	1,000,000
Stage 3		17	1.7	47.2	1,000,000 (did not fail)
CP Grade 2 Ti Beam B6					
Stage 1	38	17	1.7	44.7	1,000,000
Stage 2		25	2.5	65.8	30,000 (failed)

1 kip = 4.448 kN

The maximum and minimum load values were calculated such that they fall within 22 and 45% of the maximum predicted flexural static failure load of the corresponding test beam. The stress ratio (R), which is the ratio of the minimum load to the maximum load for the fatigue tests, was fixed to be 0.1. A summary of the maximum load and minimum load for each test beam is provided in Table 2. The predicted failure load for each fatigue test beam is also listed in the table along with ratio of maximum load to ultimate load (P_{max}/P_u) for purpose of reference. Owing to the limited number of fatigue test specimens available for this research project, the tests were initiated at a higher percentage value of the static failure load than would normally have been done, had there been a larger sample number for the purpose of testing.

The test beams were inspected periodically during the fatigue tests to fully ensure that there was no sign or trend of visual cracking or other related visible damage to the beam due to repeated loading. Particular attention was paid to the locations of the welds, fixtures, and loading hardware. The number of cycles, actual load level, and corresponding deflection recorded by the MTS controller were carefully monitored to see if there is either a progressive reduction in the load or an increase in deflection with an increase in the number of cycles.

7. Results and Discussion

The beams designated as B5 and B6 were the two commercially pure titanium (Grade 2) welded built-up test beams that were tested to study and establish the fatigue behavior.

7.1 Beam B5 [CP Titanium (Grade 2)]

The first beam that was tested with the objective of studying fatigue behavior of the built-up titanium beams was Beam B5. It was a challenge to determine the appropriate ratio or fraction of the ultimate load for the test beam primarily because of the lack of prior research work performed either by the authors or other researchers, and documented in the open literature. The concept of built-up welded titanium beams fabricated using the GMAW-P process is untested so far. Therefore, fatigue testing was initiated at a fairly high ratio, i.e., 55% of the ultimate load to a maximum load (P_{max}) of 20 kips (89 kN) and a minimum load (P_{min}) of 2.0 kips (8.9 kN) with the prime objective of observing fatigue response of the test beam. The test beam was observed to deflect rigorously at this fraction of the ultimate load. Consequently, the test was paused after the beam was loaded to just over 35,000 load cycles. Immediately thereafter, the load fraction was reduced to 22.2% of the ultimate load with a maximum load of 8 kips (35.6 kN) and a minimum load of 0.8 kips (3.6 kN). The fatigue test was observed to be smooth following a reduction in the ratio of maximum load to 22%. The test was stopped when the total number of cycles reached one million. The percentage of maximum or ultimate load was then increased to 47.2% with the objective of initiating fatigue failure. However, the beam was able to withstand another one million cycles. The fatigue test was classified to be a run-out test since the built-up welded beam did not fail even after 2 million load cycles. A careful visual observation of the beam at several key locations spanning the regions of the metal (beam) and the weld region did not reveal visible signs of distress.

After completion of the fatigue test, Beam B5 was then loaded in a static test setup and deformed to failure under the influence of a static load. The test results corresponding to the static load test, which is a residual strength test after run-out in the fatigue load test, can be found elsewhere (Ref 6).

7.2 Beam B6 of CP Titanium (Grade 2)

The fatigue test on Beam B6 was initiated at a high ratio of ultimate load, i.e., 44.7%, with a maximum load (P_{max}) of 17 kips (75.6 kN) and a minimum load (P_{min}) of 1.7 kips (7.6 kN). After 320,000 cycles, the test was stopped due to failure of the left support, i.e., breaking of the fastener/bolt that was used in the support fixture. The test was re-started following replacement of the broken fastener with a high strength fastener. The fatigue test ran smoothly following this initial glitch at this high ratio of the maximum load to safely complete one million load cycles. There were no visual signs of distress or cracks at locations of the weld and the beam elements. Further, there was no evidence of an increase in deflection at this stage. With an intention of causing failure during the fatigue test, the ratio or fraction of the ultimate load was increased to 65.8% so as to enable us understand the macroscopic failure mode and underlying microscopic mechanisms governing failure. The beam deflections were noticeably large, and the beam revealed marginal vibrations to accommodate the large central deflection at a loading frequency of 5 Hz. Eventually, the beam failed when nearing ~30,000 cycles. Failure of the beam occurred by the initiation of a crack at the bottom of the beam and consequently, breaking into two pieces.

Since the occurrence of failure was rapid, it was not possible to instantaneously capture the actual failure mode. The overall failure mode of this beam (B6) when deformed at a high ratio, i.e., 65.8% of the maximum load, is shown in Fig. 6. From this figure, it is evident that cracking, which initiated at the bottom flange presumably at locations of the weld, was responsible for triggering the onset of failure.

Fig. 6 Fatigue failure of Beam B6

8. Failure-Damage Analysis

A careful examination of the fatigue fracture surfaces of the deformed and failed beam (B6) in a scanning electron microscope revealed the specific role of intrinsic microstructural features and related microstructural effects in governing fatigue behavior of the test beams. Representative fracture features of the failure planes of the test beams made from commercially pure titanium (Grade 2) are shown in Fig. 7 and 8.

On a macroscopic scale, fracture of the test beam at locations of the weld section was essentially flat and along the far-field load axis (Fig. 7a). A careful and thorough observation of the different regions of the fracture surface was made at the higher allowable magnifications of the SEM with the objective of delineating the intrinsic fracture features. High magnification observations of the deformed and failed fracture surface revealed large areas to be essentially transgranular (Fig. 7b). The transgranular region when observed at higher magnifica-

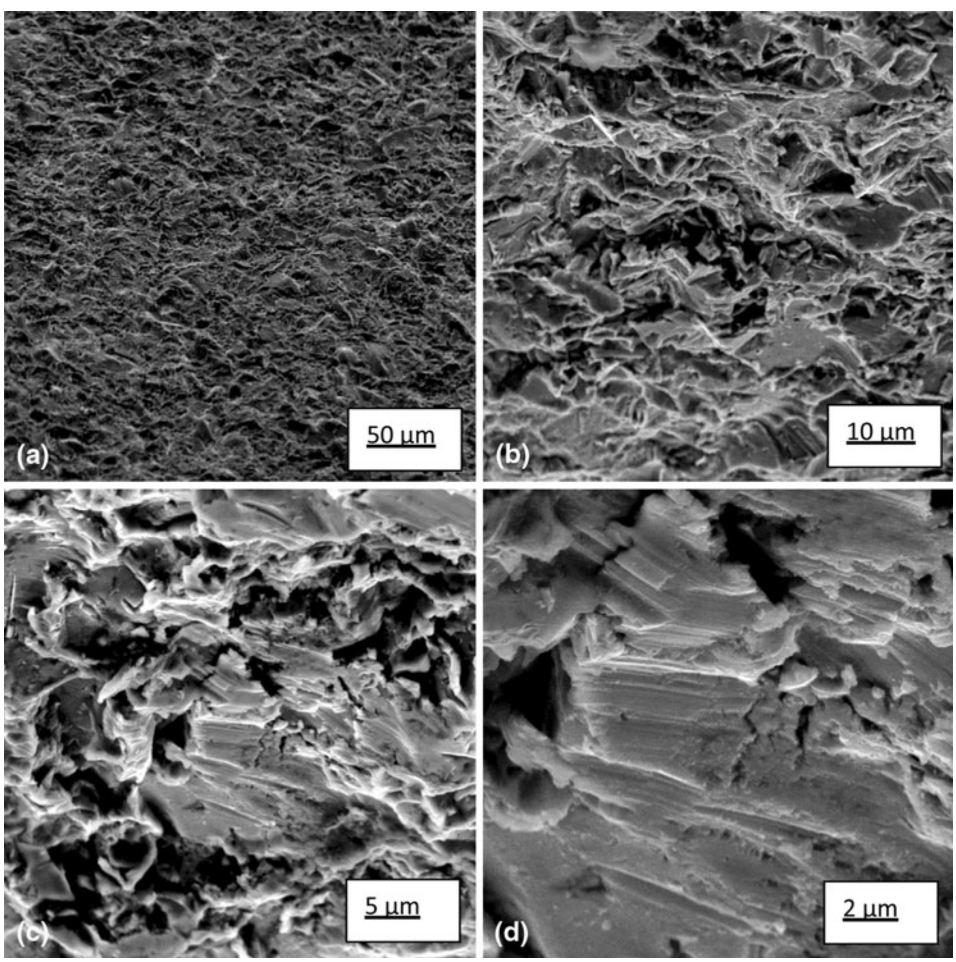

Fig. 7 Scanning electron micrographs of the beam web section of the commercially pure titanium (Grade 2)—Beam B6 after failure, showing: (a) overall morphology; (b) high magnification of (a) showing transgranular region; (c) pockets of shallow striation in the transgranular region reminiscent of microplastic deformation; (d) high magnification of (c) showing the nature and morphology of the striations

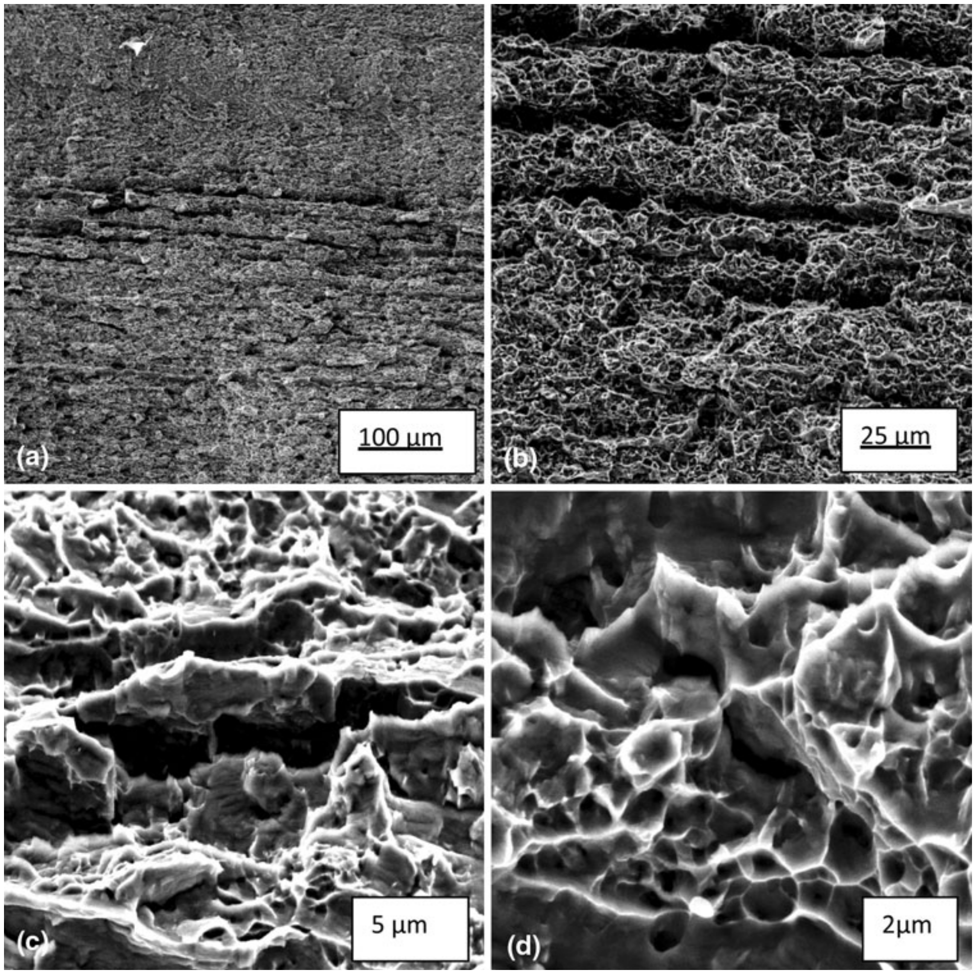

Fig. 8 Scanning electron micrographs at the region of the beam flange section of the commercially pure titanium (Grade 2)—Beam B6 after failure, showing: (a) overall morphology of the fracture surface in this region; (b) high magnification of (a) showing an array of coplanar cracks; (c) transgranular region at a higher magnification showing nonlinear microscopic crack; (d) void coalescence to form a micrographic crack and a health population of dimples facets in the region of crack initiation and early crack growth

tion revealed pockets of striations (Fig. 7c) reminiscent of microplastic deformation occurring at the ''local'' level. High magnification observation of the pockets of striations revealed them to be essentially ''shallow'' and limited in number with random orientation (Fig. 7d) in conformance with texture of the microstructure.

In the region of the beam-flange section, the features revealed by the scanning electron microscope are shown in Fig. 8. Overall morphology was essentially flat (Fig. 8a). The observation of the transgranular fracture surface at higher magnifications revealed an array of co-planar macroscopic cracks (Fig. 8b). At still higher magnifications, the fine microscopic cracks were observed to be essentially nonlinear as they progressed through the fracture surface (Fig. 8c). In the region of unstable crack growth, the fine microscopic voids coalesced to form a microscopic crack, and the surface was covered with a population of shallow dimples (Fig. 8d), features reminiscent of ''locally'' brittle and ductile failure mechanisms. The region of early microscopic crack growth revealed fine striations reminiscent of localized microplastic deformation (Fig. 9).

The presence of (i) grain boundaries, (ii) grain boundary triple junctions, and (iii) trace amounts of coarse and intermediate size

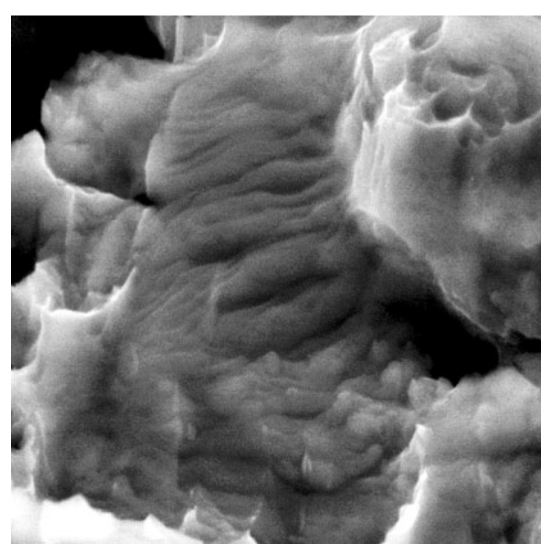

Fig. 9 Scanning electron micrographs at the region of beam flange section of the commercially pure titanium (Grade 2)—Beam B6 after failure, showing fine striations reminiscent of localized microplastic deformation in the region of early microscopic crack growth

intermetallic particle arising from the residual amounts of tramp elements or impurities in CP titanium (Grade 2) and distributed both in the matrix and along the grain boundary regions, are the potential sites for the localization of stress at selected points through the microstructure of the parent metal and regions of the weld. The corresponding built-in strain is conducive for the following:

(i) Early nucleation and concurrent growth of the microscopic voids through cracking of the coarse and intermediate size particles.
(ii) Their gradual growth and eventual coalescence with each other to form fine microscopic cracks that were well distributed through the fracture surface.

The halves of these voids are the shallow dimples visible on the fracture surface. Growth of the fine microscopic cracks during repeated loading and their eventual coalescence results in macroscopic crack. The plastic deformation that is occurring at the ''local'' level is responsible for aiding the growth of these fine microscopic and macroscopic cracks through the microstructure. Since crack extension under the direct influence of an external load occurs at the high ''local'' stress intensities comparable with the fracture toughness of the chosen material (CP titanium (Grade 2)), the presence of fine microscopic voids resulting from cracking of the particles during repeated loading coupled with cracks, both microscopic and macroscopic, has a detrimental influence on resistance of the microstructure to fatigue damage, particularly at locations of the weld.

9. Conclusions

Based on this study on the use of *p*ulsed *g*as *m*etal *a*rc *w*elding (GMAW-P) process for the manufacturing of beams made from commercially pure titanium (Grade 2), the following are the key findings:

1. With the latest GMAW-P welding technology developed by the US Army at Picatinny Arsenal, it is feasible to fabricate large welded built-up titanium beams by welding parts together to achieve good structural fatigue performance.
2. The welded beam concept used in this study worked well for the titanium beams tested in the project. It is anticipated that the concept of welded built-up beams will be both attractive and applicable for the manufacture of large structural members made from commercially pure titanium (Grade 2).
3. The fatigue tests performed on the test beams revealed that the welded built-up beams of commercially pure titanium (Grade 2) have good fatigue life. The commercially pure titanium (Grade 2) Beam B5 was able to withstand a total of two million cycles without failure or distress occurring either in the parent metal or the welds. The first million load cycles for the beam was at a ratio of 22.2% the ultimate load, and the next one million cycles corresponded to a ratio of 44.7% the ultimate load. The test beam (B6) was able to withstand one million cycles at a load ratio corresponding to 44.7% the maximum load. This is considered to be ''good,'' considering that the structure is a built-up beam that has been bonded together by welding.
4. Macroscopic fracture of the test beam at locations of the weld section was essentially flat and along the far-field load axis. High magnification observations of the deformed and failed fracture surface revealed large areas to be transgranular. The transgranular region revealed pockets of shallow dimples reminiscent of microplastic deformation occurring at the ''local'' level. The pockets of striations were ''shallow'' and limited in number and randomly oriented in conformance with the texture of the microstructure.
5. In the region of the beam-flange section, the overall morphology was essentially flat. The transgranular fracture surface at higher magnifications revealed an array of co-planar microscopic cracks. The fine microscopic cracks were observed to be essentially nonlinear as they progressed through the fracture surface. In the region of unstable crack growth, the fine microscopic voids coalesced to form a microscopic crack, and the surface was covered with a population of shallow dimples, features reminiscent of ''locally'' brittle and ductile failure mechanisms. The region of early microscopic crack growth revealed fine striations reminiscent of localized microplastic deformation.

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