Residual stresses and fatigue behavior of hybrid butt welded joints

C. Casavola, C. Pappalettere, F. Tattoli, F. Tursi

Politecnico di Bari, Dipartimento di Ingegneria Meccanica e Gestionale, Viale Japigia, 182 – 70126 Bari

casavola@poliba.it

Abstract: Ti6Al4V alloy combines mechanical strength, deformability, excellent fatigue and corrosion resistance and high strength to weight ratio. Furthermore, the mechanical behavior remains excellent at high temperature. Such characteristics make this material attractive for numerous applications (structural, aerospace and naval) because of recent improvements in welding techniques (laser, hybrid laser/MIG) that allow realizing high quality titanium welded joints. However some problems related to the welding, as deteriorated material properties, residual stresses and distortions, need further investigations. Residual stresses can have a significant influence on the fatigue life of structural engineering components. For the accurate assessment of fatigue life a detailed knowledge of the residual stress profile is required. This paper presents a study on residual stresses of Ti6Al4V butt plates welded by hybrid laser/MIG process. Residual stresses were measured by hole drilling method using electrical strain gage rosettes bonded at different position, in order to evaluate magnitude and distribution of residual stresses along the cord. Residual stresses curves obtained are presented and discussed in terms of transversal and longitudinal residual stresses. Residual stresses were also measured at surface by means of X-ray diffractometer. Besides residual stress measurements, this paper presents experimental fatigue results on titanium grade 5 butt welded joints. The fatigue curves expressed in terms of nominal amplitude of stress (according to the traditional global method) and in terms of local amplitude of strain (according to the local Wel.Fa.Re. method) have been plotted after the experimental tests. Electrical strain gauges bonded close to the weld toe have been used to calculate the local strain amplitude. The aim of this work is to present experimental data related to welding processes in order to confirm the validity of currently procedures or improve them.
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**Key words:** Residual stress, hybrid welding, fatigue performance, Ti–6Al–4V, butt joints

1. **INTRODUCTION**

Titanium and its alloys are widely applied because of their favorable strength to weight ratio and their resistance to corrosion in oxidizing environments [1, 2]. The high corrosion resistance is caused by passivation due to a thin oxide layer that naturally cover the surface. Titanium alloys welded joints fabricated for several applications such as automotive, chemical implants, aerospace, military vehicles, are often subjected to fluctuating loads. This kind of loading causes small cracks to grow during life of the component and leads to fatigue failure. A detailed study of fatigue behaviour of the material could prevent unexpected failures. Welding of titanium alloy is complicated due to the high reactivity of this material with atmospheric gases such as oxygen, nitrogen and hydrogen causing severe embrittlement of the joint [3]. Because of its high level of specific power and the limited area involved, laser technology appears to be a promising solution. The laser beam sources of the new generation are capable of producing deep and narrow seams. However, the laser welding process leads to a non-uniform temperature distribution and associated thermal strains, which generate residual stresses due to melting and subsequent cooling of the weld and surrounding material [4]. Eboo [5] showed that an addition of electric arc to the laser beam used for welding and cutting could decrease the needed power of laser with respect to the case when only laser is used for welding. This technique combines the best characteristics of both laser and arc welding processes, acting simultaneously in the same process zone [6]. The advantages of the hybrid welding technique compared to pure laser welding or arc-welding are well known and include an increase in (a) the welding speed, (b) the weldable material thickness, (c) the gap bridging ability, and (d) the welding process stability and efficiency [7]. In particular, laser-arc hybrid welding offers many advantages for heavy industrial applications involving thick-walled materials as it enables full penetration weld of thick plates without the need of multiple passes and at that reduces welding after works such as cutting for adjustment and fairing at the assembly stage. Hybrid welding improves productivity by two to four times as compared to the conventional arc welding [6]. In addition, in the fusion zone of hybrid laser-arc welding, equiaxed grains exist, whose sizes are smaller than that obtained from arc welding but larger than those from laser beam welding. Welding process unavoidably involves a stage of residual stress in the welded structure that could lead to some problems in terms of dimensional stability and structural integrity. Because of the variety of factors involved in welded parts, it is very difficult to predict and control...
residual stresses caused by welding. Residual stresses can have a significant influence on the fatigue lives of engineering components [8]. In particular, near surface tensile residual stresses tend to accelerate the initiation and growth phases of the fatigue process while compressive residual stresses close to a surface may prolong fatigue life. Significant advances have been made in recent years for obtaining accurate and reliable determinations of residual stress distributions.

Fatigue strength of welded joints is lower than base material because of microstructure modifications, misalignment, geometrical discontinuity of the cord, residual stresses and weld defects. In order to take into account all the variables affecting the fatigue strength, the fatigue design of welded components is done on the basis of experimental results, using fatigue curves available in codes [9].

The fatigue behavior of an α + β Ti6Al4V alloy butt welded by hybrid technique has been investigated in this paper. The experimental results have been compared with a previous study on similar welded joints, but obtained with different process parameters [10-11]. Fatigue fracture surface have been observed by scanning electron microscope. Besides in this paper experimental hole drilling method and X-ray diffraction measurements have been reported.

2. MATERIAL AND METHODS

The material used in the tests was titanium grade 5 (Ti6Al4V), an α−β alloy with aluminium that is an α-stabilizing element and vanadium that is a β-stabilizing element. Ti6Al4V has good mechanical properties both at room and high temperature. Its density is half steel density (4.4 kg/dm³ [2]), the ultimate strength is 980 MPa and the yield strength is 760 MPa. Titanium grade 5 mechanical properties and chemical composition are indicated in tables 1 and 2.

| Table 1: Mechanical properties of grade 5 titanium alloy [12] |
|---------------------------------|----------------|----------------|----------------|----------------|
| Yield strength (MPa)            | Ultimate strength (MPa) | Young’s Modulus (MPa) | Elongation at fracture (%) |
| 760                             | 980             | 110200        | 14             |

| Table 2: Chemical composition of titanium grade 5 according to ASTM B265 [2] |
|---------------------------------|----------------|----------------|----------------|----------------|
| Element                        | C        | Al    | V     | Fe   | H    | N     | O    |
| %                              | < 0.08   | 5.5– 6.75 | 3.5– 4.5 | < 0.30 | < 0.015 | < 0.03 | < 0.25 |

At room temperature, unalloyed titanium has a hexagonal close-packed (hcp) crystal structure called α-phase. At 883 °C this transforms to a body-
centered cubic (bcc) structure called $\beta$-phase. The manipulation of these crystallographic forms with alloy elements and thermo-mechanical processes is the base for the developing of a wide variety of alloys with different properties.

The weld cord is smooth and regular, but it has a golden coloration which indicates a partial oxidation of the cord surface. A filler material with the same chemical composition of the plates has been used during the joining process.

In welded structures, the residual stress values vary from one point to another and the measurement needs to be carried out in different positions. The measurement is usually executed on panels designed specifically for this purpose. The most common specimen, if not explicitly specified otherwise, is a rectangular, butt-welded panel. Since the panels are being designed for testing purposes only, even a destructive test can be considered if this facilitates the measurement considerably [13].

The HDM is the most widely used technique for residual stress measurement. The principle involves introduction of a small hole at the location where residual stress is measured. Due to drilling of the hole, residual stresses are relieved and the corresponding strains on the surface are measured using strain gauges bonded around the hole. From these measured strains, residual stresses are calculated using appropriate calibration constants derived for the particular type of strain gauge rosette used. For HDM measurements type B strain gage rosettes are bonded close to the weld cord, with the hole at 2 mm from the weld line. The drilling was carried out in a series of small steps (20 steps in 1 mm). A high-speed air turbine and carbide cutters were used to drill the hole without introducing any further machining stresses and thereby modifying the existing stress system. The strain data at pre-determined depths were precisely acquired. Different stress calculation methods are used to arrive at the residual stress system from the measured strains. In this case, the integral method with Tikhonov regularization of H-DRILL software has been used to measure the variation of the residual stresses through the thickness.

The XRD method is the most common non-destructive method to determine the surface residual stress in crystalline materials. XRD is accurate, but it is limited by the fact that only information is obtained about a relatively thin surface layer. The XRD-$\sin^2 \psi$ technique was developed from the theories of crystallography and solid mechanics. Given the limited penetration of X-rays in solid surfaces, what the XRD-$\sin^2 \psi$ technique measures is the surface residual stress in a depth of up to a few micrometers. For XRD measurements, XSTRESS 3000 equipment [14] and the $\sin^2 \psi$ method have been utilized; TiK$\alpha$ radiation ($\lambda = 2.2909 \, \text{Å}$) is used as X-ray source. XRD residual stress measurement has been performed on the transversal direction to the weld cord of butt welded plates. The collimator with 1 mm illuminated spot size has been used and the exposure time has
been set at 90 sec to ensure the adequate intensity. The operation voltage and current were 30 kV and 6.7 mA. The 110-diffraction of titanium with the diffraction angle of 137.4° has been analyzed. During the stress measurement, ψ (the angle between the diffraction vector and the normal to the surface) of 0°, 19.3°, 27.9° and 35° have been selected to plot d (interplanar spacing) – sin2ψ curves on both positive and negative ψ range. Considering the texture effect on the stress measurement, a ψ oscillation with ±3° has been used during the measurement. Indeed, to give reliable values of residual stress, measurements have been replicated on the same points.

Fatigue specimens have rectangular geometry, with the cord positioned in the middle. Experimental tests have been carried out on a RUMUL Vibro-Forte resonant machine 500 kN capacity. The load applied has a constant amplitude and load ratio equal to 0.1 and the work frequency is 60 Hz. The tensile fatigue load has been applied along the direction normal to the weld cord. Before the execution of the test two electrical strain gauges have been bonded on each side of the cord in order to measure strain values and to calculate the local amplitude of strain. 1.5 mm grid length strain gauges have been used in this study and they have been bonded with their transversal axes at 1 mm from the weld toe.

The Wel.Fa.Re. method utilises the local strain amplitude εa measured at the weld toe [15-21] because it presumes that this parameter can include the effects of all variable influencing the fatigue life of welded joints. The local strain amplitude is measured before the fatigue test applying a static nominal load amplitude. Consequently, with the execution of the fatigue tests it is possible to obtain the fatigue life curve expressed in terms of local strain amplitude εa:

\[ \epsilon_a = \frac{\epsilon_{\text{max}} - \epsilon_{\text{min}}}{2} \]

and in terms of nominal stress amplitude σa:

\[ \sigma_a = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \]

Four electrical strain gages have been bonded on the specimens according to the Wel.Fa.Re. guidelines. The value of local strain has been measured at the weld toe. System 5000 by Micro Measurements Inc. (USA) has registered strain gages measured values.

There are several approaches to study the fatigue behaviour of welded joints. The global methods and FEM analysis can characterize the overall strength of the joints, but their models are often too simple and do not consider important aspects such as material inhomogeneity due to changes in microstructure, residual stresses due to temperature gradients and local stress
concentrations. Recently, Eurocode Standard [22, 23] has introduced the Hot Spot method, but only for steel and aluminium alloys. The correct evaluation of the fatigue strength for complex geometries remains a difficult task and in some cases only the local methods based on experimental measurements can correctly interpret all the factors that affect the strength of welded structures.

3. TEST PLAN

Geometry of welded plates and locations of residual stress measurements are shown in Figure 1 and Figure 2. Residual stress measurements have been carried out by means of HDM and XRD on the welded plate before the cutting of specimens for fatigue tests. The thickness of the welded plate was 3 mm; six specimens 40 mm width and 400 mm long have been cut from the butt welded plate using the milling cutting procedure. Outer sides of plates have been removed because of defects and welding irregularities.

![Figure 1. Geometry of welded plates and location of drilled holes in HDM](image1)

![Figure 2. Geometry of welded plates and location of XRD measurements](image2)

Table 4 shows the plan of fatigue tests.
Before the execution of the tests the $\alpha$ angle (figure 3) has been measured in order to evaluate the secondary bending effect on fatigue tests. The distortion of the plates is caused by the welding thermal cycle. The heating
and subsequent cooling of a narrow area and the gradient of temperature imposed to the plate are the causes of distortions and residual stresses in the welded joints.

Table 4: Fatigue test plan

<table>
<thead>
<tr>
<th>Joint geometry</th>
<th>Plate thickness [mm]</th>
<th>Number of specimens</th>
<th>Welding technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt</td>
<td>3</td>
<td>6</td>
<td>Hybrid (Laser + MIG)</td>
</tr>
</tbody>
</table>

Figure 3. Distortion angle on the specimen after the weld process.

Table 5 reports the values of the distortion $\alpha$ angle measured on the specimens obtained from the four welded plates. The $\alpha$ angle has a very low value with a mean value of 0.23°.

Table 5: Distortion angle $\alpha$ measured on the test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Distortion angle $\alpha$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.12</td>
</tr>
<tr>
<td>A2</td>
<td>0.06</td>
</tr>
<tr>
<td>A3</td>
<td>0.20</td>
</tr>
<tr>
<td>A4</td>
<td>0.32</td>
</tr>
<tr>
<td>A5</td>
<td>0.19</td>
</tr>
<tr>
<td>A6</td>
<td>0.49</td>
</tr>
</tbody>
</table>

| mean value | 0.23 |
| standard deviation | 0.15 |

4. RESULTS AND DISCUSSION

Figure 4 and Figure 5 show HDM calculated residual stress respectively in the transversal and longitudinal directions with respect to the weld cord of the hybrid butt welded plate.
Stresses are plotted against the hole depth h. Plotted residual stresses are calculated by Integral method. Tensile stresses are produced in either direction and it was found that the longitudinal residual stresses are higher than transversal residual stresses. These characteristics agree well with the results reported in the literature (Figure 6). A welding process generates a significant residual stress in the longitudinal (welding) direction, $\sigma_y$, that generally has a peak tensile stress in the center of the weld bead and a peak compressive stress in lateral zones (Figure 6). At the same time, stress in the transversal direction is present, $\sigma_x$; this reaches lower values with respect to the stresses acting in the longitudinal direction (Figure 6). If the lateral contraction of the joint is restrained by an external constraint such as a series
of springs, tensile stresses approximately uniform along the weld are added as the reaction stress. An external constraint, however, has little influence on the distribution of longitudinal residual stresses. Regarding possible symmetries, a panel designed conveniently for measuring residual stress will have a double symmetric geometry (xz and yz symmetry planes in Figure 6). This, however, does not imply a complete symmetry of temperature field during the welding process. The joint in fact is not realized simultaneously along its length and differences can be found between the areas at the beginning and at the end of the joint. Therefore some "strange" values, measured longitudinal to the cord at the hole 1 and hole 2 (Figure 5) probably are due to this phenomenon.

Figure 6. Typical distributions of residual stresses in butt welded plate [13]

Figure 7 shows values of residual stress normal to the weld cord of the hybrid butt-welded plate in the case of XRD measurements. In this case, locations of measurements have been chosen in the center of the plate, at progressive distance from the weld cord. XRD values are commonly referred to the surface of specimen. Figure 7 also shows residual stress level measured by HDM in the direction normal to the cord at intermediate location between the first two points of XRD measurements near the surface (0.033 mm depth) in case of hybrid butt plates. Residual stress measured by means of HDM gives the average stress related to the area (the hole diameter range between 1.8 and 2.0 mm) where the material is drilled (the area corresponding to the hole drilled by HDM is marked in Figure 7). It can be observed that the XRD measurements no. 1 and 2 are localized at 0.5 and 3 mm from the weld line, while HDM hole cover the area between 1 and 3 mm from the cord, due to the inherent limitation laying in the size of strain gage
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Residual stress levels given by HDM (about 60 MPa corresponding to 0.033 mm depth) seem to be an intermediate value.

![HYB_XRD](image)

*Figure 7. Calculated residual stresses normal to the cord on hybrid butt welded plate by XRD*

The results of the experimental fatigue tests are reported in table 6.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Nominal Stress Amplitude $\sigma_a$ [N/mm$^2$]</th>
<th>Local Strain Amplitude $\varepsilon_a$ [$\mu \varepsilon$]</th>
<th>Cycles to Failure $N$</th>
<th>Final Crack Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>80.6</td>
<td>700</td>
<td>151390</td>
<td>Weld cord</td>
</tr>
<tr>
<td>A2</td>
<td>85.6</td>
<td>800</td>
<td>142497</td>
<td>Weld cord</td>
</tr>
<tr>
<td>A3</td>
<td>60.5</td>
<td>512</td>
<td>589342</td>
<td>Weld cord</td>
</tr>
<tr>
<td>A4</td>
<td>50.4</td>
<td>487</td>
<td>2181159</td>
<td>Weld defect</td>
</tr>
<tr>
<td>A5</td>
<td>55.0</td>
<td>519</td>
<td>1533205</td>
<td>Weld defect</td>
</tr>
<tr>
<td>A6</td>
<td>52.5</td>
<td>539</td>
<td>1313911</td>
<td>Weld defect</td>
</tr>
</tbody>
</table>

It should be noted that the fatigue failure occurs within the weld cord, or near weld defects such as drops of fused material when they are presents. Similar results have been obtained in previous works [10, 11, 24] and they confirm the susceptibility of titanium to this kind of defects.

The fatigue strength of titanium grade 5 welded joints is also strictly dependent to the joining process parameters. Figures 8 and 9 show the fatigue curves, for a load ratio of 0.1, expressed in terms of nominal amplitude of stress $\sigma_a$ and local amplitude of strain $\varepsilon_a$, according to the Wel.Fa.Re. method, of two different series of welded joints, welded both by hybrid technique, but with different parameters. “A” series has been studied in this work, “B” and “C” series are reported in a previous work [10].
Experimental data are fitted with a power law of Basquin’s type where the number of cycles to failure increases as a negative power function of stress range $\sigma_a$ and of the local amplitude of strain $\varepsilon_a$.

![Fatigue curve $\sigma_a - N$.](image)

**Figure 8.** Fatigue curve $\sigma_a - N$.

![Fatigue curve $\varepsilon_a - N$.](image)

**Figure 9.** Fatigue curve $\varepsilon_a - N$.

It can be noted that “A” series has lower fatigue strength compared to “B” and “C” series, and this result is due to different set of parameter in the joining process. The fatigue resistance for “A” series butt joints is lower of about 28% in terms of nominal amplitude of stress and of about 35% in terms of local amplitude of strain.

Figure 10 shows some the fatigue final fracture paths that are localized within the weld cord (butt A2, butt A3) and near drops of fused metal (butt A4). Crack initiation is highly affected by these defects and fatigues cracks initiate always from these sites if they are present.
In spite of the presence of these welding defects, fatigue curves expressed in terms of both nominal amplitude of stress and in terms of local amplitude of strain are well correlated. It should be noted that for the “A” series the correlation factor is higher for the nominal amplitude of stress fatigue curve and this result is different for “B” and “C” series. The different grid length of strain gages used could cause it. In fact, in this work, 1.5 mm grid length has been used in order to measure the strain near the weld toe instead of 3 mm grid length used for “B” and “C” series. The strains are measured in a smaller area more closely to the weld cord. However the fatigue failures didn’t occur always within the weld cord or at the weld toe and a shorter grid length integrates the strains in smaller area in order to capture the local effect near the weld toe. For this reason, in this case, the local amplitude of strain can describe the fatigue behaviour of titanium grade 5 welded joints only in a partial way.

The analysis on the cross section of the fatigue failure surfaces by using a scanning electron microscope (SEM) has been carried out using a ZEISS evo microscope. Fractographic observations have been performed using the SEM operating in the secondary electron mode. In particular, the spacing of the fatigue striations on the fracture surfaces have been observed on surfaces perpendicular to the incoming electron beam. These observations were intended to give an indication of the local fatigue crack initiations and propagation during the test. Specimens have been cut and prepared in order to obtain the sample suitable for this kind of analysis. The effect of drops of fused metal distant from the weld cord has been investigated observing the cross section of the final fatigue fracture initiate from this site.

Figure 11 shows some fractographic observations on the fatigue fracture surface for the specimen Butt A2.
In this case, the fatigue failure occurs within the weld cord, and it can be noted the presence of porosity within the fused zone (Figure 11c). However the main crack responsible for fatigue failure is not localized near the porosities, but in the lower part of the specimen (Figure 11d). Figure 11a shows the fatigue striations and Figure 11b is the observation of zone with the static failure. The initiation of the main fatigue crack, can be noticed in Figure 11d. This result indicates that fatigue cracks can initiate in correspondence of weld defects, but the final failure can depend on other causes such as the local geometry of the weld cord and sharp notch present on the cord surface can influence more the fatigue strength of titanium grade 5 butt welded joints.

Figure 12 shows some fractographic observations on the fatigue fracture surface for the specimen Butt A4.
In this case, the fatigue failure occurs near the drop of fused metal (Figure 12a), from this site it can be noticed the main fatigue crack. Figures 12b and 12c show the fatigue striations in different zones of the cross section, and Figure 11d shows a global observation obtained by the SEM microscope of the fracture surface. The fatigue crack growth rate is lower in Figure 12b and 12c, compared to Figure 12a. The higher crack propagation rate noticed in Figure 12a can be attributed to the presence of the fused metal drop that increases the stress concentration.

5. **CONCLUSION**

Hybrid (laser/MIG) butt welded joints have been considered in this work. Residual stress measurements have been executed by means of X-ray diffractometer, which gives a concentrated localized value of stress. Measured points are located along a direction transversal to the cord. Analysis of residual stresses measured values suggests the following considerations:

- HDM measurements on hybrid butt welded plate show that tensile stresses are produced in the transversal and longitudinal directions with respect to the weld cord and that longitudinal residual stress are higher than transversal residual stresses. These characteristics agree well with the results reported in the literature.
- Regarding possible symmetries, a panel designed conveniently for measuring residual stress will have a double symmetric geometry. This, however, does not imply a complete symmetry of temperature.
field during the welding process. The joint in fact is not realized simultaneously along its length and differences residual stress can be found between the areas at the beginning and at the end of the joint.

- Tensile stresses in the transversal directions with respect to the weld cord near the cord become compressive distant from the weld cord.
- Stress level measured near the surface in the direction normal to the cord by XRD on hybrid butt plate are in good agreement with the stress level relived by HDM measurements.

The fatigue behaviour of butt hybrid welded joints in titanium grade 5 has been studied. $\sigma_a - N$ and $\epsilon_a - N$ fatigue curves have been obtained. $\epsilon_a - N$ fatigue curve has been plotted according to the Wel.Fa.Re. method recommendations: two electric strain gauges have been bonded with their principal axes at 1 mm from the weld toe for each weld cord, then the local amplitude of strain is calculated applying the maximum and the minimum load of the fatigue test.

The local strain amplitude can account for the effects of many factors influencing fatigue life of welded joints and that the nominal stress concept could not appreciate. However in this case, the fatigue failures didn't occur always within the weld cord or at the weld toe and the local amplitude of strain can describe the fatigue behaviour of titanium grade 5 welded joints only in a partial way.

Finally a comparison with the fatigue resistance of Ti6Al4V butt hybrid welded joints from a previous work has been presented. The fatigue resistance of titanium hybrid welded joints is strictly dependent to joining process parameters.

REFERENCES


residual stresses caused by welding. Residual stresses can have a significant influence on the fatigue lives of engineering components [8]. In particular, near surface tensile residual stresses tend to accelerate the initiation and growth phases of the fatigue process while compressive residual stresses close to a surface may prolong fatigue life. Significant advances have been made in recent years for obtaining accurate and reliable determinations of residual stress distributions.

Fatigue strength of welded joints is lower than base material because of microstructure modifications, misalignment, geometrical discontinuity of the cord, residual stresses and weld defects. In order to take into account all the variables affecting the fatigue strength, the fatigue design of welded components is done on the basis of experimental results, using fatigue curves available in codes [9].

The fatigue behavior of a $\alpha + \beta$ Ti6Al4V alloy butt welded by hybrid technique has been investigated in this paper. The experimental results have been compared with a previous study on similar welded joints, but obtained with different process parameters [10-11]. Fatigue fracture surface have been observed by scanning electron microscope. Besides in this paper experimental hole drilling method and X-ray diffraction measurements have been reported.

2. MATERIAL AND METHODS

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