Static and Fatigue Characterization of Titanium Alloy Welded Joints

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ABSTRACT

Titanium and its alloys presents an elevated strength/weight ratio, good mechanical properties at high temperatures, elevated resistance to corrosion and to most part of acid attacks. These characteristics, thanks to recent improvements in welding techniques that allow the realization of high quality welded joints, makes this material attractive for numerous applications. Naval industry, for which the corrosion constitutes a discriminating element in the choice of materials, is studying new applications for the titanium.

Fatigue strength of titanium alloys is the most important information needed for naval structural applications, but none official standard similar to Eurocode exists and data available in literature are still not sufficient for a reliable fatigue design.

This work is focused on the study of static and fatigue behavior of butt welded joints in titanium grade 2 and grade 5, all obtained by laser welding technique. The experimental results of fatigue tests are presented both in terms of nominal stress amplitude σ_a and local strain amplitude ε_a.

Key words: titanium alloy, fatigue strength, welded joints.

INTRODUCTION

The increasing use of titanium in different environments, as chemical, aerospace, naval industry and orthopaedic applications, is justified by its properties. In fact, titanium has both high mechanical properties and nearly perfect compatibility with human tissue. At room temperature, titanium grade 2 (known as commercially pure titanium) has a density of 4,5 kg/dm^3, while titanium grade 5 has 4,4 kg/dm^3 [1]. Tensile strength of these alloys can reach 1300 MPa depending on the chemical compositions and heat treatments.

Besides, titanium shows excellent corrosion resistance in aggressive environments thanks to a thin protective oxide layer of TiO_2 easy to remove.

Naval industry supports researches that may improve the use of titanium: high tensile strength and corrosion resistance are required specially for building ship hull structures that have to undergo high speed (which means high stresses) and sea air attack. Titanium coatings of ship bottoms are already realized as protection against corrosion, instead of the traditional protective paints utilized on steel hull, which can pollute if dissolved in sea water.

Welding represents a good alternative to the mechanical joining for metals and their alloy. The most common methods for joining titanium alloys are laser welding, tungsten inert gas welding and electron beam welding. Because of the affinity of this material with atmospheric gases as oxygen, nitrogen and hydrogen, special devices are required during welding operations in order to protect the melting pool with inert gases.

Although welding contributes to make lighter the structure and avoids the use of holes that are dangerous for crack propagation, a weld cord is a discontinuity in the structure and modifies stress distribution. Stresses increase near the notch and distortions, misalignments and residual stresses are consequent of thermal welding cycle [2–3].

Design of welded joint is rather complicated. The weld toe can be considered as a geometrical discontinuity that modifies stress distribution. Stresses near weld toe are higher than nominal stress and locally they can exceed even yield limit. The interaction of different factors affects the fatigue limit of welded structures by generating a stress concentration near the weld toe: local and global geometry of the cord, micro structural modifications subsequent to welding thermal cycle, distortions and misalignment due to material heating and cooling, residual stresses. The evaluation of welded joints fatigue life is very complex because of all these parameters involved. The official standard may give important suggestions only for steel and aluminium structures, but no rules are actually known for titanium alloys.

In this work laser welded joints in titanium grade 2 and titanium grade 5 (Ti6Al4V) are studied. In particular, macrographies and contouring of butt joint by mechanical feeler pin were carried out in order to study welding geometries; then static and fatigue tests were carried out. Fatigue strength curves in terms of both local strain amplitude, according to WEL.FA.RE. method [10-15, 17, 19], and nominal stress amplitude are reported.

MATERIALS

Titanium alloys can be classified as either α alloys (hexagonal crystal structure), β alloys (body centred cubic structure) and α + β alloys. Alpha alloys (titanium grade 2) are characterized by satisfactory strength, toughness and weldability, but poorer forgeability than β alloys. The properties of α – β alloys (titanium grade 5) can be controlled through heat treatment. Ti-6Al-4V is an α - β alloys with aluminium that is an α – stabilizing element and vanadium that is a β – stabilizing element. The final microstructure and mechanical properties depend either on the initial temperature of heat treatment and on cooling time [4]. The microstructure of titanium can be very complex depending on the cooling time.

The chemical compositions of the tested materials ae reported in the Tabs. 1 and 2.

Before the execution of the welding, titanium plates were subjected to heat treatment and subsequent cooling in air as reported in Figs. 1 and 2.

	C	Fe	H	N	O
ASTM B 265	< 0,08	< 0,30	< 0,015	< 0,03	< 0,25
Top	0,006	0,028	0,002	0,007	0,104
Bottom	0,005	0,029	0,002	0,008	0,104

Table 1 – Chemical composition of titanium grade 2

	C	Al	V	Fe	H	N	O
ASTM B 265	< 0,08	5,5 – 6,75	3,5 – 4,5	< 0,30	< 0,015	< 0,03	< 0,25
Top	0,006	6,32	4,08	0,028	0,002	0,007	0,104
Bottom	0,005	6,25	4,08	0,029	0,002	0,008	0,104

Table 2 – Chemical composition of titanium grade 5

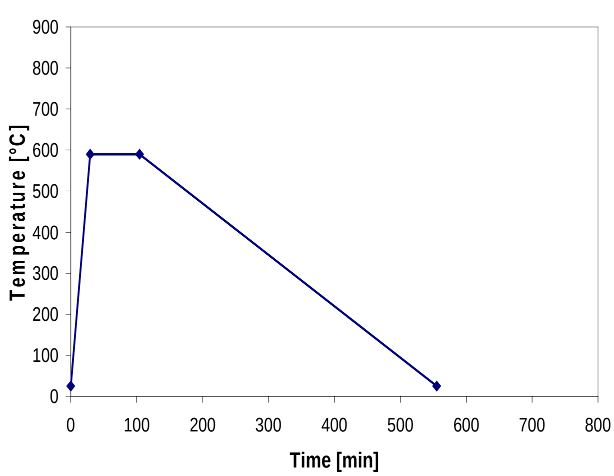

Fig. 1 – Thermal treatment for titanium grade 2

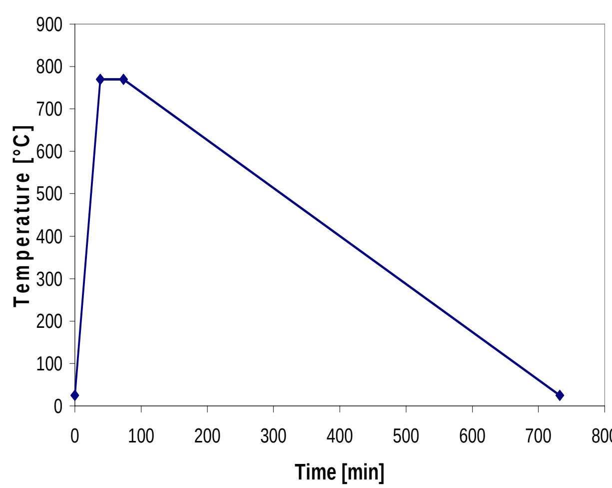

Fig. 2 – Thermal treatment for titanium grade 5

Before welding operations, titanium plates were accurately treated by lapping and chemical etching of edges. Then laser welding were executed without filler metal. The equipment used has the neodymium (laser Nd – YAG) as active material. The other welding parameters are indicated in Table 3.

Welding parameters	Titanium grade 2	Titanium grade 5
Laser beam power [W]	1600	2000
Advancing speed [mm/min]	3000	1500
Plasma gas suppression	Elio 4.8	Elio 4.8
Shielding gas	Argon 5.0	Argon 5.0
Prewarm [°C]	20	20

Table 3 – Laser welding parameters

During welding operations, all plates were constrained in 3 point in order to avoid the opening of the junction. The weld traces were subsequently cross out by the next welding passage.

Welding of titanium is not easy due to its high reactivity to atmosphere gases, so, in order to ensure weldments of good quality, a special device was utilized to prevent absorption of gases into the molten pool. This device was purposely planned to protect the fused metal till its temperature goes under 300°C. However, laser welding of titanium allows to obtain high strength joints characterized by a very narrow heat affected zone and by little distortion of welded plates thanks to titanium low thermal conductivity.

TEST METHOD

The prediction of fatigue life of welded joints is very complex because it is affected by the influence of numerous parameters as geometric variability of the cord and material inhomogeneity due to welding operations [5].

Official standards do not contemplate titanium alloys [6÷9].

Thermal welding cycle modify the microstructure of material (heat affected zone, HAZ) and cause a different hardness with respect to the base metal. In addition residual stresses are generated.

Traditional methods could be inadequate for welded structures fatigue design because they do not properly consider the influence of such parameters on fatigue strength of material. The WEL.FA.RE. method can be used to predict fatigue life of several welded joints as cruciform, angular, butt, overlap and T full penetration welded joints [10÷14].

WEL.FA.RE. method utilises the local strain amplitude ε_a measured at weld toe [15] (measuring the average strain in the area where the final fatigue rupture generally occurs [14-16]) 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 by strain gages before the execution of fatigue test at the nominal load amplitude. Consequently, the fatigue life curves at 50% safety are expressed, at fixed load ratio R, just in terms of local amplitude of strain ε_a:

$$\varepsilon_a = (\varepsilon_{max} - \varepsilon_{min})/2 \quad (1)$$

instead of in terms of nominal stress amplitude σ_a:

$$\sigma_a = (\sigma_{max} - \sigma_{min})/2. \quad (2)$$

3 mm grid length strain gages are bonded with their transversal axis at 2,5 mm from the real weld toe. This position of strain gages and their grid length result from a compromise between two requirements: the need to correctly evaluate the local strain field in the critical zone, which requires measurements in the region very close to the weld toe, and the use of a reliable and friendly experimental technique which may be transferred to an industrial environment [16-17]. Strain gauge grid location adopted in the WEL.FA.RE. method is chosen with the purpose to capture local effects due to joint global geometry, misalignments, welding local geometry, plasticity which are relevant for fatigue phenomena and can influence the strain field at the weld toe.

TEST PLAN

Misalignment measures

To evaluate the secondary bending effect on fatigue tests, on all specimens the α angle was measured (fig. 3) using a centesimal comparator.

The cord profile of butt C5 specimen was surveyed also by a high precision mechanical feeler pin (1μm accuracy) with the aim to obtain the cord local geometry (height, opening, fillet radius) and to estimate the effect of the stress concentration caused by the geometric discontinuity. The feeler pin measured the cord profile sliding along the specimen axis in orthogonal direction from the cord.

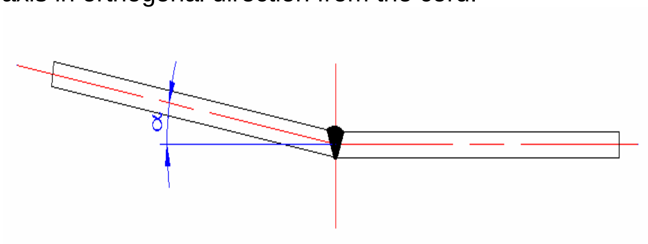

Fig. 3 - Misaligned specimen

Macrography

In order to study welding cord profile and to point out microstructure modifications due to welding, a photomacrography was executed on specimen obtained by butt C welded plate.

The preparation of the specimens for the execution of macrographies was as follow:

- Cut by cropper machine;
- Incorporation with black epoxy resin;
- Lapping;
- Polishing with nylon cloth e diamond paste;
- Chemical attack: solution HNO_3 27% / HF 3% / H_2O;

Tensile test

Static characterization was carried out on titanium grade 2 specimen with 1,5 mm thickness and on titanium grade 5 with 3 mm thickness (Tab. 4). Specimens dimensions and tests procedure agreed with RINA rules [18] for naval applications. Correct directions about titanium alloys tensile tests does not exist. The specimens for the static tests (Fig. 4) were obtained from from both Ti gr 2 and Ti gr 5 plates.

Welded plates	Thickness [mm]	Material	N° of specimens tested
Butt A	1,5	Ti grade 2	1
Butt B	1,5	Ti grade 2	2
Butt C	3,0	Ti grade 5	2

Tab. 4 – Tensile tests plan

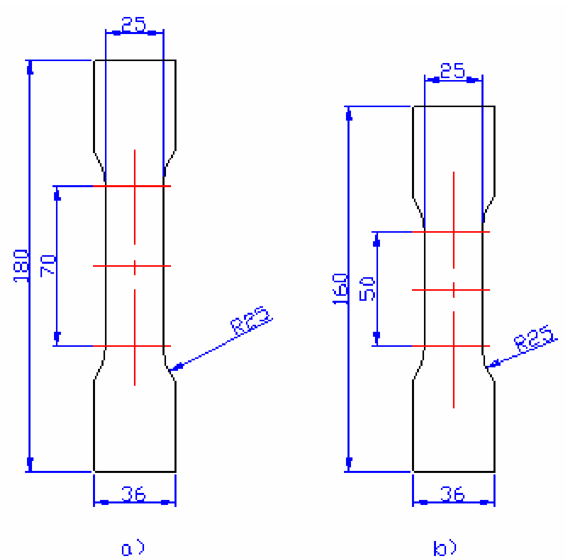

Fig. 4– Geometry of Ti Gr 5 (a) and Ti Gr 2 (b) specimens for static test

Strain gages were bonded on the two side of each specimen in order to measure the strain during the tensile test and to evaluate the secondary bending caused by occasional misalignment.
Tensile tests were performed on Instron electromechanical machine with load cell capacity of 100kN. Tests speed was 6mm/min.

Fatigue test

The specimens for fatigue tests were obtained from the same plates. Outer sides of plates were removed because of defects and welding irregularities (the cord had a golden coloration as consequence of partial oxidation caused by some problems had in protecting the extremities of the plates). Fig. 5 show geometry and type of load for fatigue test.
Fatigue tests were executed on 3 set of butt laser welded joints, as reported in Tab. 5:
Eight electrical strain gages were bonded on tested specimens according to WEL.FA.RE. guidelines: four on the welding right side and four on reverse side (Figs. 6 and 7). The amplitude of local strain was measured at the weld toe.
Before fatigue tests, visual inspections were executed on all tested specimens in order to examine the quality of the cord: no macroscopic defects were found, the cord appeared silvery (which indicates good gas protection without contaminations) and had smooth surface without evident spray.
Strain gages values were registered by System 5000 by Micro Measurements Inc. (USA).
All fatigue tests were performed under load control on a 250 kN Schenck servo-hydraulic testing machine.

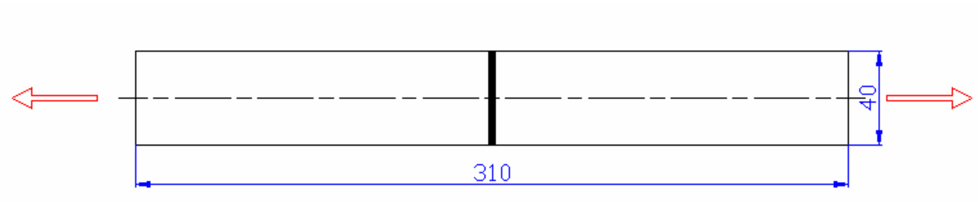

Fig. 5 – Geometry and type of load for fatigue test specimens

Series	Materials	Thickness [mm]	N. specimens tested
But A	Titanium grade 2	1,5	7
But B	Titanium grade 2	1,5	5
But C	Titanium grade 5	3,0	4

Tab. 5 – Fatigue tests plan

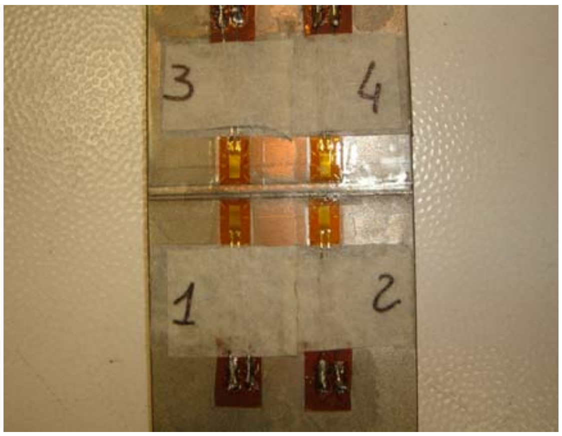

Fig. 6 – Strain gages on Ti gr 2 specimen

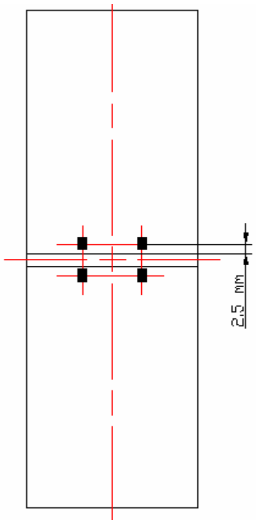

Fig. 7 – Strain gages locations

RESULTS AND DISCUSSION

Misalignment measures

The misalignment angles measured for the three tested plates A, B and C have average values respectively of 0.20, 0.31 and 0.12. This means that the plates are practically in line. These small values may be attributed to the laser welding technique and/or probably to the titanium physical characteristics. Steel joints welded by means of electric-arc generally are much more misaligned [19].

Figs. 8 and 9 represent the profile obtained by the mechanical feeler for the right and reverse side of the specimen. The cord profile appear regular and the connection with the base material both on the right side and on the reverse one is rather smooth. A small undercut was found on the right side of specimen.

The stress concentration factor k_t =1,4 was calculated from the theory of elasticity. Fatigue notch factor k_f was 1,3 but it was estimated on the base of a fatigue notch sensitivity referred to equivalent steel because no data for titanium were available. Steel joint welded by means of electric arc generally presents larger misalignments (mean value of α=1,604°; standard deviation 1,539 [these data will be included in future publication]).

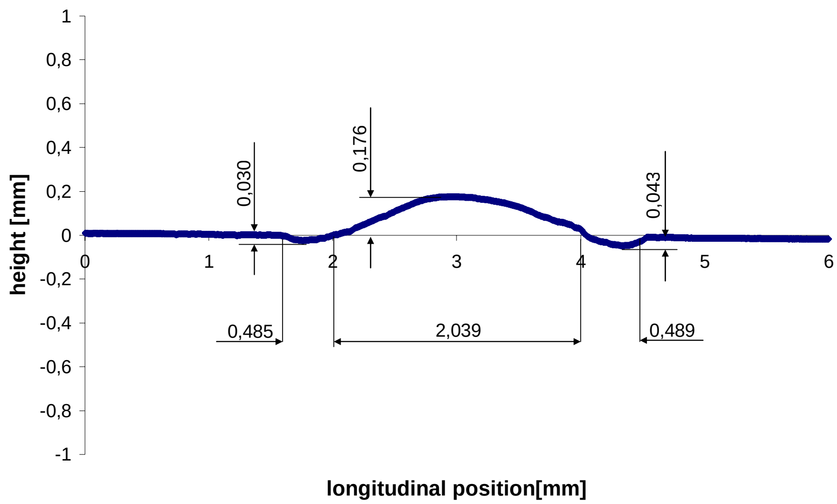

Fig. 8 – But C specimen: right side cord profile

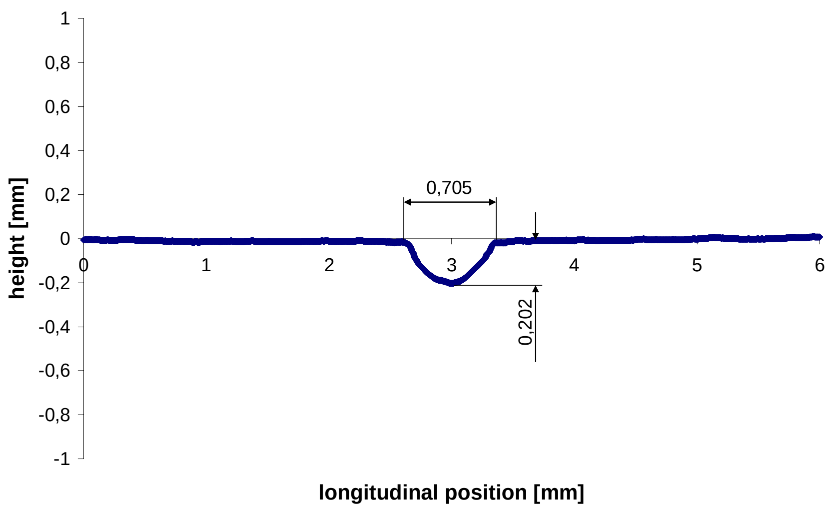

Fig. 9 – But C specimen: reverse side cord profile

Macrography

Fig. 10 shows the macrography of butt C plate welded by laser beam technique obtained by a Leica DMRME microscope. The cord is well connected on both the right and the reverse side, but a small porosity is shown.

The fused zone (with an increase in crystalline grain size) and the heat affected zone are clearly visible. A little undercut, typical of laser welding, can be observed but it appears smooth.

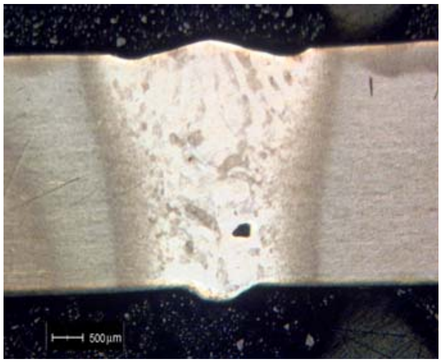

Fig. 10 - Photomacrography of titanium grade 5, thickness 3 mm

Tensile test

Mechanical characteristics obtained from tensile tests are showed in Tab. 6. Titanium grade 5 has double ultimate strength with respect to titanium grade 2, but on the contrary has a smaller ductility and an inferior elongation at break. Figs. 11 and 12 show respectively for Ti gr 2 and Ti gr 5 the graphs of the nominal stress against the strains obtained by strain gages data.

Specimen	Material	Thickness [mm]	Area [mm^2]	Modulus of Elasticity E [GPa]	Tensile Strength Ultimate R_u [MPa]	Tensile Strength Yield R_{02} [MPa]
But A9	Ti Gr 2	1,5	37,5	104,6	430,4	340
But B8	Ti Gr 2	1,5	37,5	106,9	414,1	358
But B9	Ti Gr 2	1,5	37,5	105,7	424,0	375
But C10	Ti Gr 5	3	75,0	110,2	956,4	760
But C11	Ti Gr 5	3	75,0	110,1	981,1	770

Tab. 6 – Tensile tests results

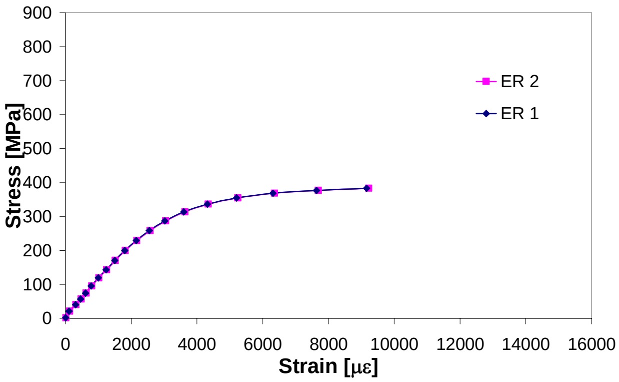

Fig. 11 – Tensile curve for titanium grade 2 (But B8)

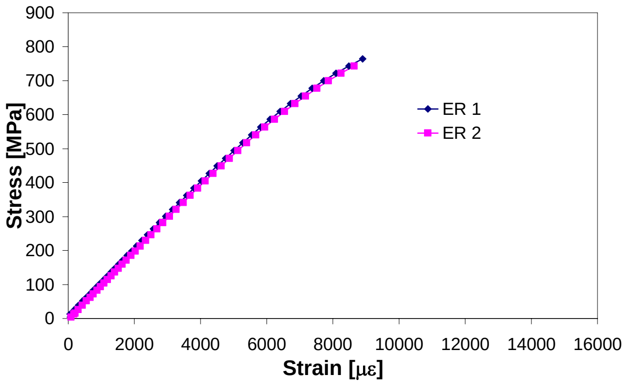

Fig. 12 – Tensile curve for titanium grade 5 (But C10)

Figs. 13 and 14 show the specimens after tensile test execution. Titanium grade 2 has a moderately ductile type of fracture: initially it was observed an elongation of specimens with a consequent section reduction, subsequently there was the growth of microscopic cracks that caused a cross-section area reduction; this central crack, with elliptical form, had its principal axis perpendicular to loading direction; the final fracture occurred at 45° when the cross-section area was no more able to withstand the applied load. Titanium grade 5 has a fragile type of fracture with moderate elongation, a not excessive reduction of cross-section area and a fracture line disposed at 45° to the load direction.

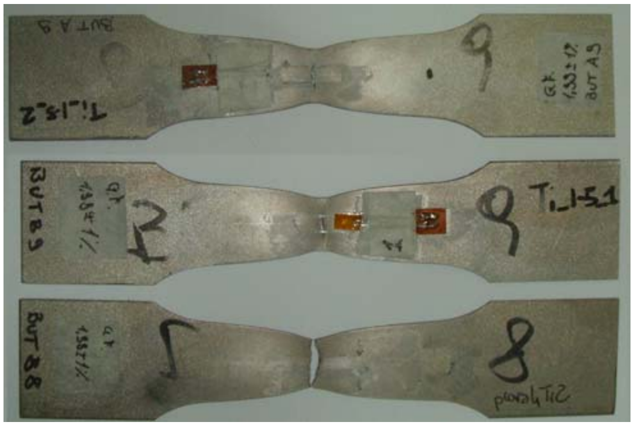

Fig. 13 - Titanium specimens grade 2 after the tension test

Fig. 14 - Titanium specimens grade 5 after the tension test

Fatigue test

All fatigue test were performed with load ratio R=0,1 and frequencies ranging in 10-15Hz.

Fatigue test results are summarized in Tab. 7. Fatigue curves in terms of nominal amplitude of stress σ_a – N and local amplitude of strain ε_a – N are reported in Figs. 15 and 16.

For all specimens (except butt C2) fatigue final fracture location occurred in the base metal zone (Figs. 17-19), away from the weld toe.

Titanium butt welded joints fatigue strength is obviously inferior than static strength. Experimental data are summarized in Tab. 8. Fatigue limit for titanium alloy is not well defined in literature nor in official standard, so reference values at 2 million, 5 million and 10 millions cycles were calculated from experimental fatigue results.

Specimen	Load Ratio $R = \sigma_{min} / \sigma_{max}$	Material	Nominal stress amplitude σ_a [N/mm^2]	Local strain amplitude ε_a [με]	Cycles to failure N	Final crack location
Butt A1	0,1	Ti Gr 2	93,5	937	780182	Base metal
Butt A2	0,1	Ti Gr 2	120	1277	95651	Base metal
Butt A3	0,1	Ti Gr 2	89,8	897	**5360199**	Unbroken
Butt A4	0,1	Ti Gr 2	113	1217	196149	Base metal
Butt A5	0,1	Ti Gr 2	91,8	950	**10494686**	Unbroken
Butt A6	0,1	Ti Gr 2	110	1112	195899	Base metal
Butt A7	0,1	Ti Gr 2	109	1123	408461	Base metal
Butt B2	0,1	Ti Gr 2	82,3	848	**10619256**	Unbroken
Butt B3	0,1	Ti Gr 2	105	1124	347080	Base metal
Butt B4	0,1	Ti Gr 2	105	1099	356141	Base metal
Butt B5	0,1	Ti Gr 2	105	1119	341022	Base metal
Butt B6	0,1	Ti Gr 2	97,5	1025	400939	Base metal
Butt C1	0,1	Ti Gr 5	100	900	**4600000**	Unbroken
Butt C2	0,1	Ti Gr 5	153	1377	332172	Weld toe
Butt C4	0,1	Ti Gr 5	142	1322	607723	Base metal
Butt C5	0,1	Ti Gr 5	133	1245	**5384500**	Unbroken
Butt C6	0,1	Ti Gr 5	137	1278	980511	Base metal

Tab. 7 - Experimental results

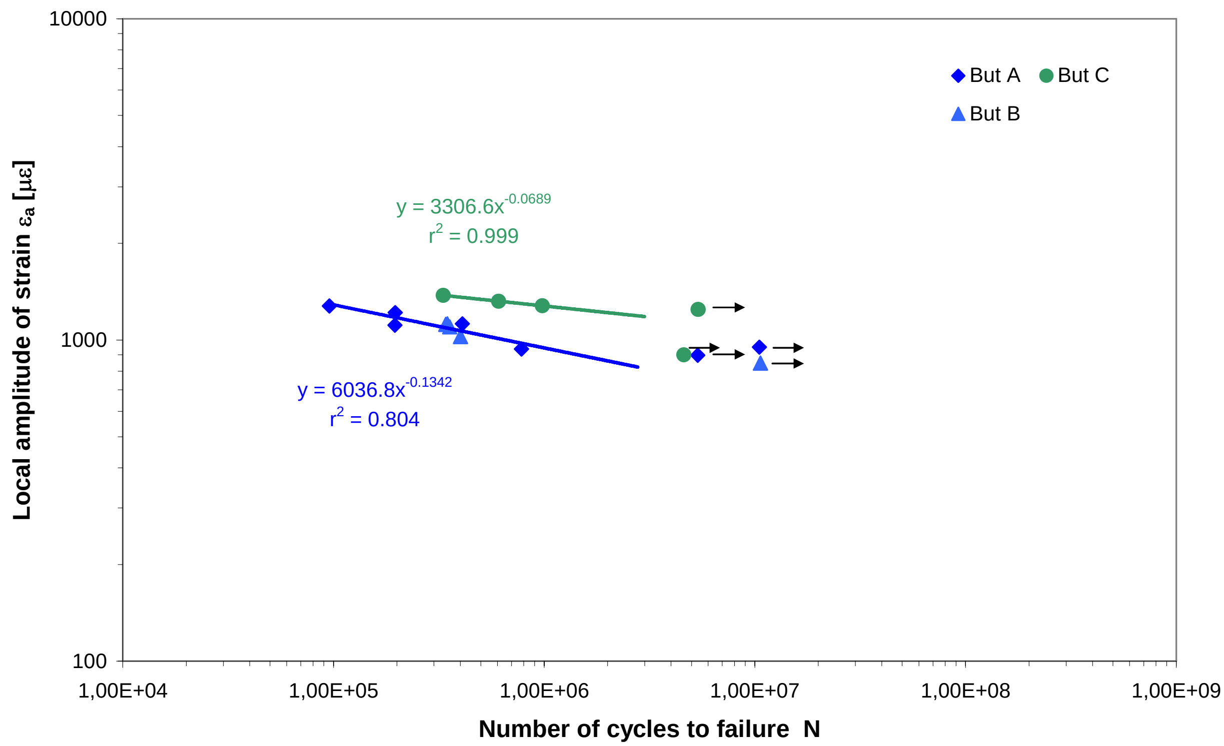

Figure 15 – Fatigue curves ε_a-N

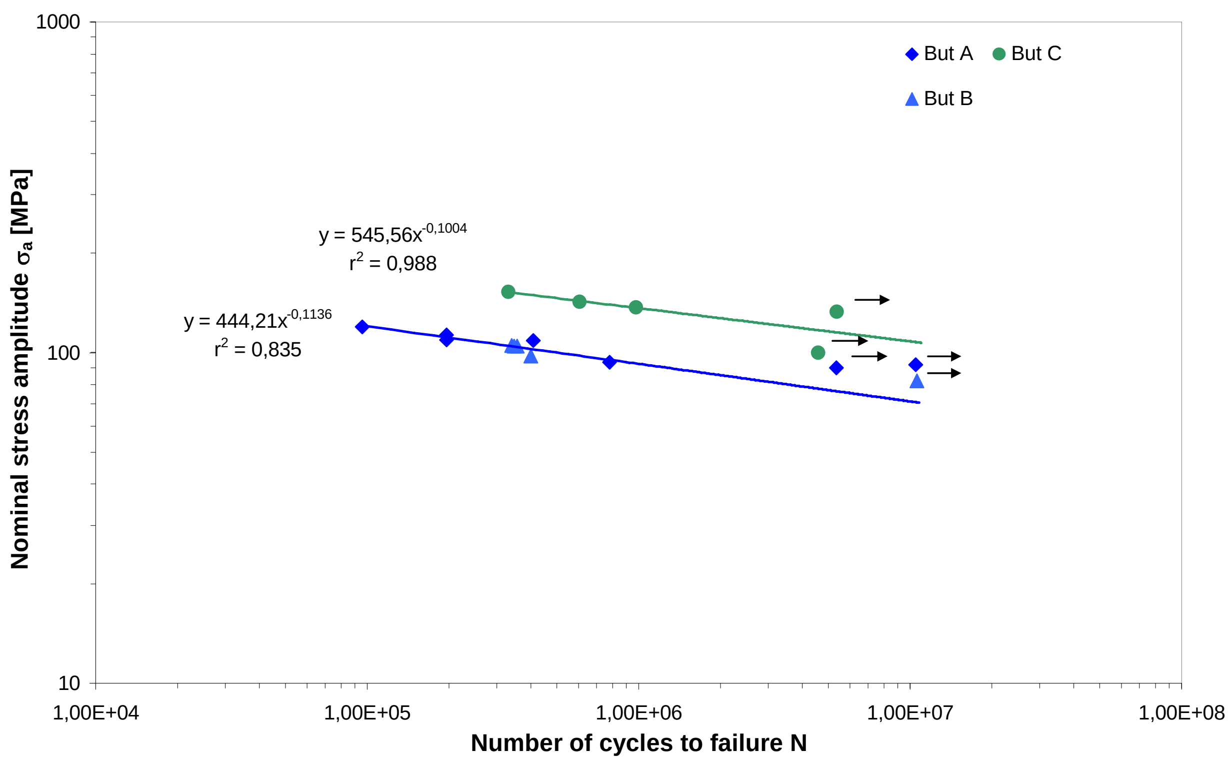

Figure 16 – Fatigue curves σ_a-N

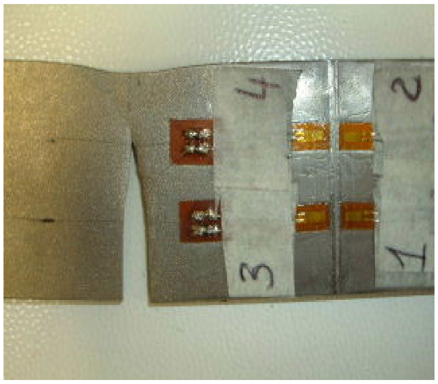

Fig. 17 – Titanium grade 2 (Butt B4)

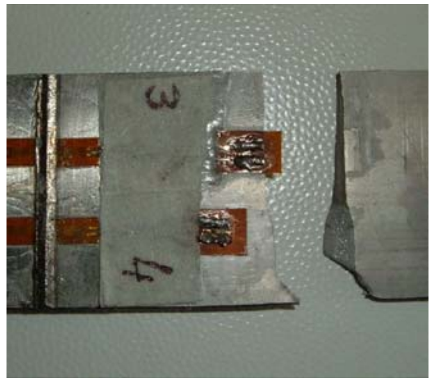

Fig. 18 – Titanium grade 5 (Butt C4)

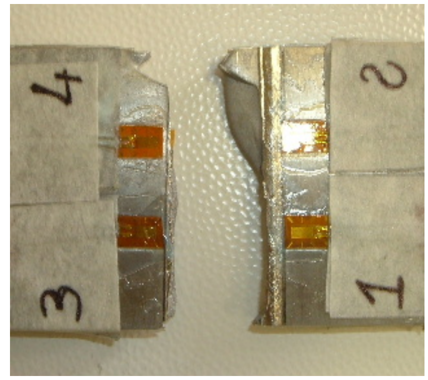

Fig. 19 – Titanium grade 5 (Butt C2)

Material	Ultimate Tensile Strength [MPa]	Fatigue strength at $N=2 \cdot 10^6$ cycles from σ_a-N curve of Fig. 15 [MPa]	Fatigue strength at $N=2 \cdot 10^6$ cycles from ε_a-N curve of Fig. 16 [MPa]	Fatigue strength at $N=5 \cdot 10^6$ cycles from σ_a-N curve of Fig. 15 [MPa]	Fatigue strength at $N=10 \cdot 10^6$ cycles from σ_a-N curve of Fig. 15 [MPa]
Ti gr 2	423	85	90	77	71
Ti gr 5	969	127	134	116	108

Tab. 8 – Tensile test and fatigue test data

Crack initiation and the final rupture are usually localized at the weld toe [12÷14]: in this area, in fact, which corresponds to the heat affected zone, the stress/strain field is amplified with respect to the nominal one because of the effects of local geometry of the cord, plasticization and secondary bending produced by misalignments.

In spite of the unusual final crack locations experimented in this work for titanium alloys, a correlation r^2 very similar in the fatigue curves both in terms of local strain amplitude and nominal stress amplitude (Figs. 15 and 16) can be observed. Also this result is unusual [10,12,14]: previous experimentation on steel welded components showed that fatigue curves in terms of strain measured at the weld toes were more correlated and more realistic in describing fatigue behaviour of welded joints than nominal stresses. But in these cases the final fracture occurred far away from the weld toes.

Then, the following considerations can be drawn:

1) Titanium specimens tested here were welded by laser beam technique, which allows smaller extension of the heat affected zone and grains dimensions interested in the thermal cycle than those produced by other welding techniques [20] with improvement of mechanical behavior and fatigue strength.

2) Titanium welded joints tested here are non at all misaligned, so secondary bending that would be captured by strain gages measurements (and included in ε_a values) but no by nominal amplitude of stresses σ_a, here cannot constitutes a discriminating element in the description of fatigue behavior as happens for steel welded joints.

3) Welding cord profile (Figs. 8 and 9) results quite regular (then stress concentration factor is quite low).

As consequence, in this case local field is not at all modified with respect to nominal one. Probably only local plasticization due to notch effects exist, but it is well known that strain gages capture only a portion of this effects by integrating it on the grid length. Probably the effect of plasticization is not very significant.

Titanium welded joints fatigue behavior appear to be well described both by nominal and local fatigue curves, the latter built by strain gage measurements that are affected by notch effects only in minimum part. It is author's opinion that fatigue behaviour is governed in a preponderant way by weld cord geometry and misalignments.

The last consideration on the location of fatigue crack follows. Ref. 21 reports Vickers hardness values measured on titanium alloy welded joints belonging to the same manufacturing lot: obviously, hardness values in the base metal are lower than in the heat affected zone. Since fatigue strength depends on the level of stress locally reached, this value is surely influenced by the material hardness value at the weld toe. The increase of local hardness imply a greater resistance at the crack nucleation. Consequently, when the hardness values in the fused and heat affected zones are very high it is more probable that the crack initiating took place in the base material [22].

CONCLUSIONS

Butt laser welded joints in titanium grade 2 and grade 5 for naval applications were studied.
The following operations were executed before any test:
- visual inspection in order to check the welding cord quality; the macrography executed confirmed this results (a small defect in the cord was found, but it did not influenced the component strength);
- measurement of the geometric characteristics: the misalignment angle between welded plates resulted very small (max mean value was 0,311°).

Static tensile tests (according to naval RINA rules) and fatigue tests were executed.
Static tests provided the mechanical characteristics of the two materials: titanium grade 5 has greater strength (σ_r = 969 MPa) and can be preferred for components hardly stressed, but it is more difficult to weld and to work by machine tools than titanium grade 2.
Fatigue tests gave the σ_a – N and the ε_a – N curves that in unusual way present a coefficient of correlation very similar. The reason of this unusual result was attributed to the limited presence of phenomena that generally modify the local field with respect to the nominal one. Final fractures, in fact, are present in the base metal zone and not at the weld toe.
It should be important to look further into this experimental investigation about titanium welded joints fatigue behavior, especially for lack of referring official standards and for the development of applications (as naval one) that need high safety requirements.

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REFERENCES

1. ASTM B265 Standard Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate, 2006.
2. Masubuchi, K., Analysis of Welded Structures, Pergamon Press, Oxford, N.York, 1980.
3. The Welding Institute, Residual Stresses and their Effects, Abington Hall, Cambidge, 1981.
4. ASM International, ASM Handbook Properties and Selection: Nonferrous Alloys and Special – Purpose Materials, vol. 2, 1992.
5. Ninh Nguyen T., Wahab M.A., The effect of weld geometry and residual stresses on the fatigue of welded joints under combined loading, Journal of Materials Processing Technology, pp. 201 – 208, 1998.
6. Eurocode 3, Design of steel structures. Part 1-1: general rules and rules for buildings, ENV 1993-1-1 European Committee for Standardisation, 1992.
7. Fatigue design and assessment of steel structures, BS 7608, London: British Standards Institute, 1993.
8. Structural welding code – steel, ANSI/AWS D1.1-86, American Welding Society, 1986.
9. Fatigue design of welded joints and components, Recommendations of IIW, XIII-1593-96/XV-845-96, Cambridge: Abington Publishing, 1996.
10. Pappalettere C., Nobile R., Fatigue Strength of Welded Joints by the Local Strain Method. Influence of Load Ratio R and Plate Thickness, Notch Effects in Fatigue and Fracture (G. Pluvinage and M. Gjonanj editors) NATO Sciences Series II – Mathematics, Physics and Chemistry, Kluwer, 307-316.
11. Dattoma V., Pappalettere C., Local Strain for Fatigue Strength of Welded Structures, J. of Strain Analysis, 2001, vol.36 (6), 605-610.
12. Casavola C., Nobile R., Pappalettere C., Fatigue strength by the WEL.FA.RE. Local Strain Method: application to 3-5 mm cruciform and butt welded joints, 2002 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Milwaukee (USA), June 10–12 2002.
13. Casavola C., Pappalettere C., Application of WEL.FA.RE. method on aluminium alloy welded joints, 2005 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Portland (USA), June 7-9, 2005.
14. Casavola C, Nobile R, Pappalettere C., A local strain method for the evaluation of welded joints fatigue resistance: the case of thin main-plates thickness, Fatigue & Fracture of Engineering Materials & Structures, 28, pp. 759-767, 2005.
15. Dattoma V., Nobile R., Panella F.W., Some considerations on the local strain amplitude used in the WEL.FA.RE. method as a design parameter against fatigue, Proceedings of the International Conference New Trends in Fatigue and Fracture II, 2003, Hammamet (Tunisia).
16. Haibach, E., Die Schwingfestigkeit von Schweibverbindungen aus der Sicht einer örtlichen

Beanspruchungsmessung, LBF – Bericht no. FB-77, Lab. f. Betriebsfestigkt, Darmstadt, 1968.
17. Casavola C., Pappalettere C., Industrial application of a new local strain method for fatigue strength evaluation of welded structures, ICEM12 International Conference on Experimental Mechanics, Bari (Italy), August 2004.
18. RINA rules, Testing procedures for materials, Section 2, Pt D, Ch 1.
19. Casavola C., Nobile R., Pappalettere C., Fatigue life predictions by the WEL.FA.RE. method: influence of residual stresses, 2003 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Charlotte (USA), June 2-4, 2003.
20. Qi Yunlian, Deng Ju, Hong Quan, Zeng Liying, Electron beam welding, laser beam welding, and tungsten arc welding of titanium sheet, Materials Science and Engineering, vol. A280, 2000.
21. Casavola C., Pappalettere C., Residual stress on titanium alloy welded joints, ICEM12 International Conference on Experimental Mechanics, Alexandroupolis (Greece), July 2007.
22. Radaj D., Sonsino C. M., Fatigue assessment of welded joints by local approaches, Abington Publishing, Cambridge, 1998.