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Caterina Casavola, V. Giordano, Carmine Pappalettere

MECHANICAL BEHAVIOUR OF AS-WELDED AND SMOOTH CORD TITANIUM WELDED JOINTS

MEHANIČKO PONAŠANJE ZAVARENIH SPOJEVA TITANA SA NEOBRAĐENIM I SA GLATKIM LICEM KONTURE ŠAVA

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Adresa autora / Author's address:
Dipartimento di Ingegneria Meccanica e Gestionale,
Politecnico di Bari, Italy, email: casavola@poliba.it

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- titanium
- hybrid welding
- WELFARE method
- welded joint

Ključne reči
- zamor
- titan
- hibridno zavarivanje
- WELFARE metoda
- zavareni spoj

Abstract

This work aims to study the fatigue behaviour of hybrid welded joints made of titanium alloy. Butt welded joints with plate thickness of 5 mm are compared to butt welded joints of plate thickness 3 mm smoothed to the cord. All specimens are realized with a hybrid welding technique. The fatigue strength of specimens is analysed in order to plot fatigue curves both in terms of nominal stress and local strain amplitude, according to the WELFARE method. Experimental tests show that the fatigue strength is highly dependent on structural variations, defects and imperfections near to the cord, due to an inadequate welding process. Superficial imperfections as fused material drops, are nevertheless eliminated through filing the cord; in this way an increase of the fatigue strength can be obtained. Smooth specimens with plate thickness of 3 mm result in having longer life duration than specimens with thickness of 5 mm. Moreover, 3 mm thickness hybrid welded joints with a grinded cord seem to have the same behaviour in fatigue resistance as laser welded joints of the same thickness. However, even after the filing, some kinds of defects as internal micro bubbles in the cord, or welding spots, continue to reduce the life of titanium hybrid welded joints.

Izvod

U radu se proučava zamor hibridnih zavarenih spojeva legure titana. Sučeoni zavareni spojevi debljine 5 mm se porede sa sučeonim spojevima debljine ploče 3 mm sa glatkom površinom lica šava. Svi uzorci su ostvareni postupkom hibridne tehnike zavarivanja. Analizirana je zamorna čvrstoća uzoraka i iscrtane su krive zamaranja s obzirom na nominalni napon i lokalnu amplitudu deformacije, a prema WELFARE metodi. Eksperimenti pokazuju da zamorna čvrstoća u velikoj meri zavisi od promena u konstrukciji, defektima i greškama oko konture šava, usled neadekvatnog postupka zavarivanja. Površinske greške, kao što su prokapljine, se eliminišu brušenjem šava, i na ovaj način se postiže povećanje zamorne čvrstoće. Uzorci sa glatkom površinom, debljine 3 mm kao rezultat imaju duži vek od uzoraka debljine 5 mm. Osim toga, hibridni zavareni spojevi debljine 3 mm sa brušenim licem šava pokazuju slična svojstva otpornosti prema zamoru kao i laserski zavareni spojevi iste debljine. Međutim, čak i nakon brušenja, neke vrste defekata, kao što su unutrašnji mikro mehurovi u šavu, ili pore, i dalje ugrožavaju vek hibridnih zavarenih spojeva legura titana.

INTRODUCTION

Using welded joints instead of mechanically connected joints has become recently a good way to reduce the weight of structures and to provide metallic continuity in the structure, thus conferring properties in the joint that are quite equivalent to those of the metal being joined (mechanical, thermal, chemical, electrical). Moreover, the insertion of bolts, nails or rivets, needs passing holes that leads to a weakening of the structure. Stress concentrations generated in proximity of holes and discontinuities reduce the fatigue strength of components. To increase the fatigue resistance, wider thickness has to be used, increasing in this way the structural weight. A solution, recently found, is the combination of materials of different thicknesses obtained with new welding techniques, or the positioning of more resistant materials at locations of higher stresses, /1/. A new trend in the mechanical design imposes the use of materials with a high strength/weight ratio, so in the last years industries consider replacing heavier materials by lighter ones, e.g. in the automotive industry steel is replaced by aluminium, magnesium, or carbon reinforced polymers. Not always these materials ensure an optimal strength for all kinds of stresses involved during the working of the component.

Because of its properties, titanium and its alloys tend to be more useful than aluminium or magnesium. In fact titanium is half weight, but also the strength of the best classes of steel. In addition to this, it has high corrosion resistance comparable with platinum, a fusion temperature close to the refractory materials, and perfect biocompatibility, /2-3/.

For all these reasons the double effect of the welding of joints and the use of a low density material as titanium alloy Ti-6Al-4V (grade 5) can be an interesting argument of study.

Many kinds of welding operations are nowadays possible, but in this work the hybrid welded joints are analysed, making a brief comparison with laser welded ones.

The welding operation is not always easy for titanium joints, because of the high reactivity with atmospheric gases that can produce defects like inclusions or cavities. Also thermal gradients are introduced in a welded joint with geometrical discontinuities that debilitate the joint. A way to increase the strength of the joint may be the smoothing of the cord through the grinding operation.

The aim of the present work is the comparison of the fatigue strength between hybrid welded titanium joints made of titanium grade 5 with plate thickness of 5 mm and welded titanium joints made of the same alloy with plate thickness of 3 mm, with a smoothed cord. Fatigue curves are plotted both in terms of local strain and nominal stress amplitude and are compared.

The stress field close to the weld toe is investigated in order to verify how microstructural variations within the cord and defects related to the welding operation may change the mechanical behaviour of the components.

METHODS AND MATERIALS

Many parameters affect the welding process and complicate a phenomenon already extremely complex as the fatigue behaviour of joints. Because of the thermal cycle of welding, the microstructure of the material changes, favouring a more fragile behaviour.

Both analytical-numerical approaches and experimental approaches are adopted for studying the stress and the strain fields. Analytical and numerical approaches can give an immediate idea of the behaviour of the joint, but sometimes refer to simplified cases that do not pay attention to material inhomogeneity (due to the welding procedure because the heat affected zone and the melting zone are generated into the cord), and residual stresses (connected to the rapid cooling after the welding process). Those methods are often based on simplified geometries of models (too far from the shape of real components) and generally neglect the real geometry and microstructure of the weld toe, /4/. Experimental measurements with a local approach, instead, seem to be able to take into account all the local effects that modify the behaviour of the joints.

The use of strain gauges that measure the local strain, can pick the effects of total and local geometry, including the effect of joint thickness, the presence of misalignments and distortions, or the shape of the cord. Methods based on the measure of local strain amplitude choose the local strain as an useful parameter for the evaluation of the fatigue damage, /4-7/. In particular, the strain amplitude ε_a, measured from strain gauges in the proximity of the weld toe, under static loading, is considered the most meaningful data for fatigue tests, according to the WELFARE method, /5-6/.

Hybrid welded joints

The object of study specimens have been obtained from plates made of titanium grade 5, welded without filler metal and without the gap between the welded plates. A hybrid technique, that means a simultaneous use of laser and MIG (Metal Inert Gas) techniques, is adopted. Advantages of the hybrid process include higher welding stability, higher melting efficiency and lower power input under the same penetration. Moreover, the laser allows a complete penetration and a high welding speed and the MIG technique avoids long time in edge preparation, /8-9/.

Joints obtained with the hybrid technique have a larger heat affected zone, compared with laser welded ones, /5/, and a classical “Y shape” due to the two-fold effect of MIG, that generates the upper cone, and of the laser, that penetrates deeply with a focused beam, /8/. Comparing the cord, it can be noted that, in laser welded joints it does not present evident defects or sprays. Hybrid welded ones, instead, often present external drops of fused material, on or near the cord. A mechanical tactile device (±1 μm accuracy) is used to obtain the profile in the direction transverse to the cord, both for right and reverse side of a laser welded- and of a hybrid welded joint. For this last one, the upper seam is larger and more accentuated, with a width of about 4.4 mm instead of 1.5 mm of a laser joint, and a height of about 0.6 mm instead of 0.2 mm of the laser one. Also, for a lower seam, the hybrid technique generates a larger cord, with an interesting presence of a deep undercut, verified in the laser welded joint. No undercut is, instead, observed neither on the right, nor on the reverse side of a hybrid welded specimen (Fig. 1). This will allow to grind the cord without leaving the undercut to be a critical point for stress concentration and for crack generation.

Specimens

The specimens tested have a nominal width of 40 mm, length of about 348 mm and different thickness: 5 mm for the ones with normal cord, and 3 mm for the those with the smooth cord.

The welding cord has an orthogonal direction to the longitudinal axis of the specimen and to the direction of the loading applied during the fatigue tests. A preliminary visual inspection is carried out on each joint and it has shown, in some cases, for joints of 5 mm thickness, the presence of macroscopic defects in the cord or close to it, as slobbers or spots of fused material. Obviously no prominent external defect is noted on smoothed specimens, because they have been removed with the grinding operation.

In Figure 2 are reported the right side and the reverse side of a smoothed specimen and of a classic welded specimen, respectively.

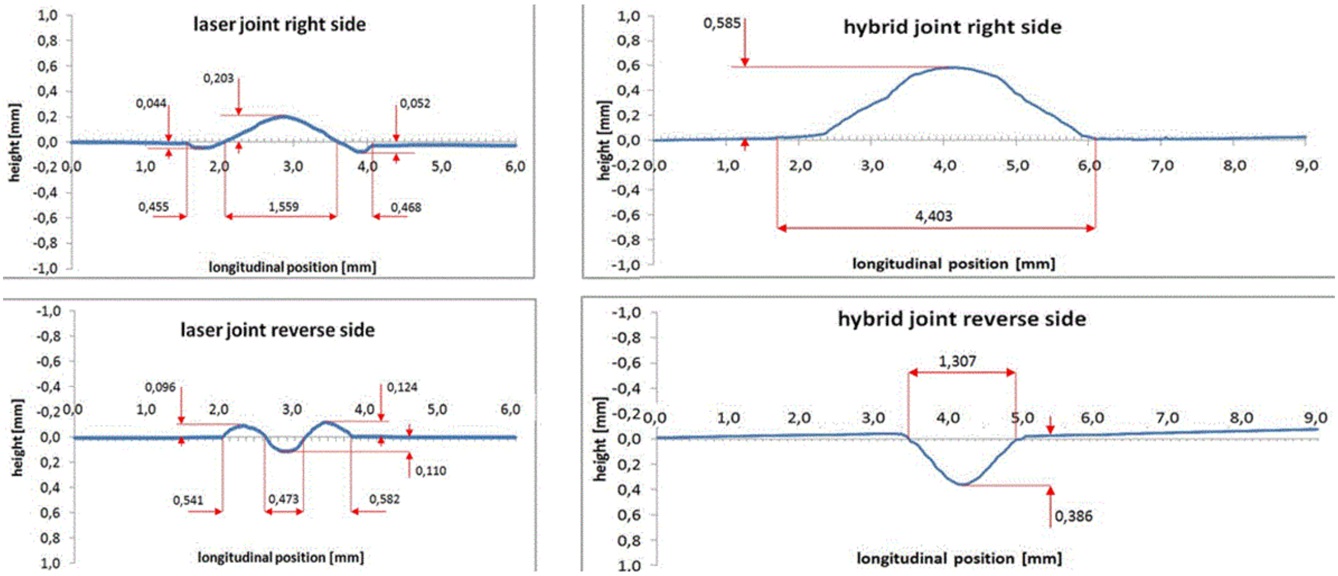

Figure 1. Right and reverse profile of a laser- and of a hybrid welded joint.
Slika 1. Desni i suprotni profil laserskog i hibridnog zavarenog spoja

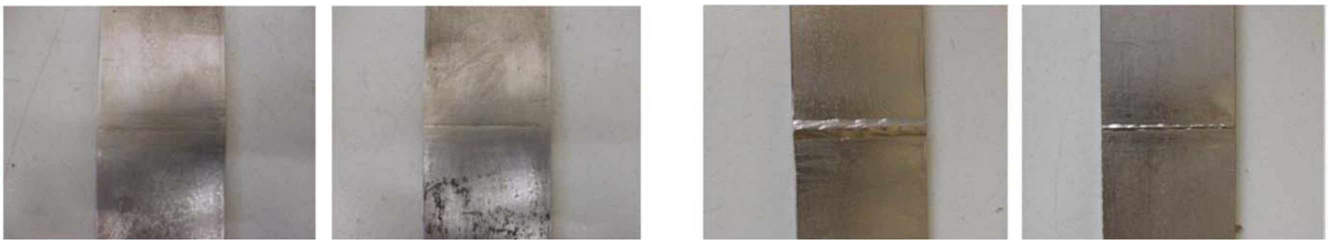

Figure 2. Right side and the reverse side of a smoothed specimen and of a classic welded specimen.
Slika 2. Desna strana i suprotna strana glatkog uzorka i klasičnog zavarenog uzorka

Table 1. Experimental results of fatigue tests.
Tabela 1. Eksperimentalni rezultati ispitivanja na zamor

Specimen	Thickness (mm)	Material	Welding technique	Joint	σ_a (N/mm^2)	ε_a (μm/m)	Cycles to failure, N	Fracture
Butt G1	3	Ti gr. 5	hybrid	smoothed	90.0	949	10.795.000	unbroken
Butt G2	3	Ti gr. 5	hybrid	smoothed	101.5	1109	10.411.800	unbroken
Butt G3	3	Ti gr. 5	hybrid	smoothed	112.5	1272	10.382.700	unbroken
Butt G4	3	Ti gr. 5	hybrid	smoothed	142.8	1416	308.200	base material
Butt G5	3	Ti gr. 5	hybrid	smoothed	135.0	1364	322.700	weld toe
Butt G6	3	Ti gr. 5	hybrid	smoothed	134.9	1327	93.200	weld toe
Butt G7	3	Ti gr. 5	hybrid	smoothed	124.0	1224	376.800	weld toe
Butt I1	5	Ti gr. 5	hybrid	with cord	80.6	800	10.000.000	unbroken
Butt I2	5	Ti gr. 5	hybrid	with cord	92.0	927	2.654.000	in vice
Butt I3	5	Ti gr. 5	hybrid	with cord	56.9	634	11.500.000	unbroken
Butt I4	5	Ti gr. 5	hybrid	with cord	100.1	1181	782.000	weld toe
Butt I5	5	Ti gr. 5	hybrid	with cord	89.1	1058	647.000	weld toe
Butt I6	5	Ti gr. 5	hybrid	with cord	91.2	1018	10.000.000	unbroken
Butt I7	5	Ti gr. 5	hybrid	with cord	112.9	1212	59.300	weld toe
Butt L1	5	Ti gr. 5	hybrid	with cord	79.2	831	1.527.300	in vice
Butt L2	5	Ti gr. 5	hybrid	with cord	83.3	897	425.000	defect on cord
Butt L3	5	Ti gr. 5	hybrid	with cord	103.2	1035	287.300	on a spot
Butt L4	5	Ti gr. 5	hybrid	with cord	68.0	808	11.000.000	unbroken
Butt L5	5	Ti gr. 5	hybrid	with cord	68.2	771	588.900	defect on cord
Butt L6	5	Ti gr. 5	hybrid	with cord	91.4	973	4.365.000	in vice
Butt L7	5	Ti gr. 5	hybrid	with cord	135.8	1439	62.700	weld toe
Butt L8	5	Ti gr. 5	hybrid	with cord	115.1	1224	195.700	on a spot
Butt M1	5	Ti gr. 5	hybrid	with cord	100.9	1063	1.048.000	weld toe
Butt M2	5	Ti gr. 5	hybrid	with cord	90.8	967	10.000.000	unbroken
Butt M3	5	Ti gr. 5	hybrid	with cord	101.5	1152	274.600	on a spot
Butt M4	5	Ti gr. 5	hybrid	with cord	94.6	1051	2.436.000	in vice
Butt M5	5	Ti gr. 5	hybrid	with cord	96.9	1125	173.000	on a spot
Butt M6	5	Ti gr. 5	hybrid	with cord	80.9	1246	62.000	weld toe

EXPERIMENTAL TESTS

Fatigue tests are performed at load ratio R = 0.1. Joints with 3 mm thickness are tested at 15 Hz frequency, instead, the tests on joints of 5 mm thickness are performed on a resonance testing machine with a frequency of about 80 Hz.

Experimental results are reported in Table 1. For each joint are reported thickness, welding characteristics and the fatigue parameters in terms of semi-amplitude of stress and local strain semi-amplitude, with a brief description of the modality of final fracture observed.

As shown in Table 1, the joints with cord, present the fatigue fracture close to defects as slobbers or spots, that result to be stress concentration points and the cause of failure. These kinds of defects are eliminated through the smoothing operation. In this way an increase of the fatigue strength can be observed. Obviously this operation cannot eliminate internal porosity and defects that for both kind of specimens result as another weak point.

Interestingly, it is to note the behaviour of the specimen Butt G4; in fact it results to be the only one specimen in which fracture has started and continued in the base material. This may confirm the idea exposed in /5/ that while in traditional materials, as aluminium or steel, fatigue fracture always occurs at the weld toe, for titanium joints, in case of an optimal welding operation, the welding cord is not the weakest part of the structure.

Unfortunately, the high reactivity of the titanium makes the welding operation very difficult, especially in case of the hybrid technique. So many specimens obtained from the studied plates present many cord irregularities or internal micro-bubbles, and no evidence of this idea can be gathered yet, but the generation of fracture in the base metal for a smoothed joint may be proof that, for Ti gr. 5 hybrid welded joints, the cord represents surely a geometrical discontinuity, and not a microstructural weak point.

Analysing data of laser welded joints taken from /5/, it can be seen that fracture has occurred in many specimens in the base metal. As known, the cord geometry for laser joints is most regular and moderate, so it may be that the cord is not a stress concentration zone, and also microstructural variation due to the welding operation is not very relevant, so failure occurs often in the base material.

COMPARISON OF SMOOTH JOINTS AND NON-SMOOTH JOINTS

Figure 3 shows fatigue curves as a relation between local strain amplitude and number of cycles to failure, both for 5 mm- and for 3 mm joints smoothed to the cord, welded with a hybrid technique. It can be noted that the slope for both curves is similar, but the smoothed joints present a fatigue strength higher than the non-smoothed ones, even if they have a lower thickness. This is surely due to the smoothing operation that eliminates the cord as a local stress concentration area, /10/, and cord irregularities or defects such as drops of melted material, or swells, due to an imperfect welding operation.

The graph in Fig. 4 reports in terms of stress amplitude and number of cycles to failure. It can be observed that the slopes of fatigue curves both in terms of local strain (ε_a-N) and nominal stress (traditional σ_a-N Wöhler curve) are very similar, this indicating that local effects, in the case of titanium welded joints with respect to traditional steel, /5-7/, do not have a relevant role, both in the case of a smooth cord and in case of joints with cord.

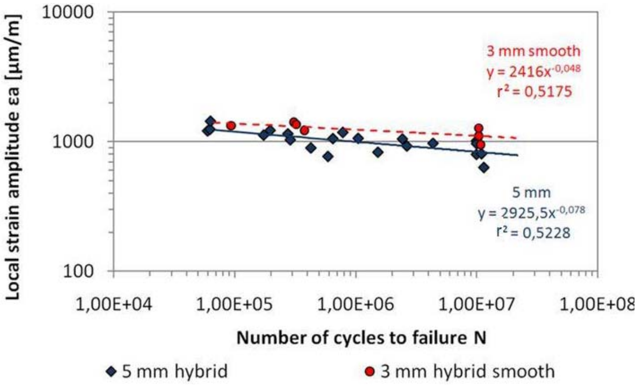

Figure 3. Fatigue curves (ε_a-N) of Ti gr 5 hybrid welded joints.
Slika 3. Krive zamaranja (ε_a-N) hibridnih zavarenih spojeva Ti gr 5

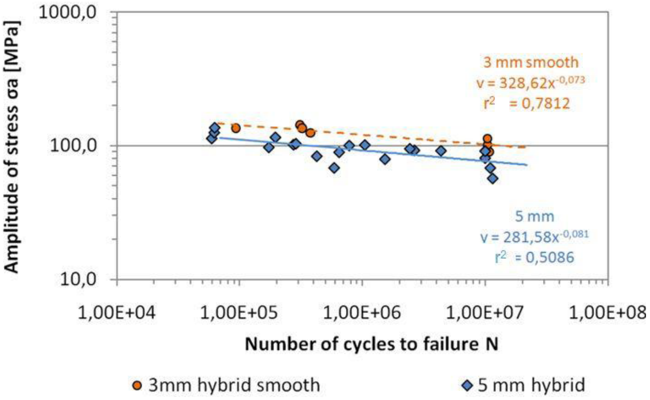

Figure 4. Fatigue curves (σ_a-N) of Ti gr 5 hybrid welded joints.
Slika 4. Krive zamaranja (σ_a-N) hibridnih zavarenih spojeva Ti gr 5

In Figure 5 the fatigue curves in terms of stress amplitude for Ti gr 5 specimens, laser welded (3 mm thickness), /5/, hybrid welded (5 mm), and hybrid welded with smoothed cord (3 mm), are compared with the results obtained for specimens of base material (3 mm). The behaviour of laser welded joints and hybrid welded ones smoothed to the cord is very similar as confirmed in the graph. The cord for laser joints is less accentuated and has not a relevant role in specimen failure. Instead, the volume of material generated on the cord with the hybrid technique is not slight, so the smoothing operation eliminates the weakness of the cord that not only represents a stress concentration zone, but also contains more quantity of material and so a statistically higher concentration of defects.

A value for a quantification of the increase of strength of joints, due to the smoothing operation, can be done through a comparison of the coefficients:

$$c_r = \frac{\sigma_I(N_f)}{\sigma_{II}(N_f)}$$

Where σ_I and σ_{II} are the stress values taken from the two different curves at the same number of cycles to failure (N_f), in Fig. 5. The results are resumed in Table 2.

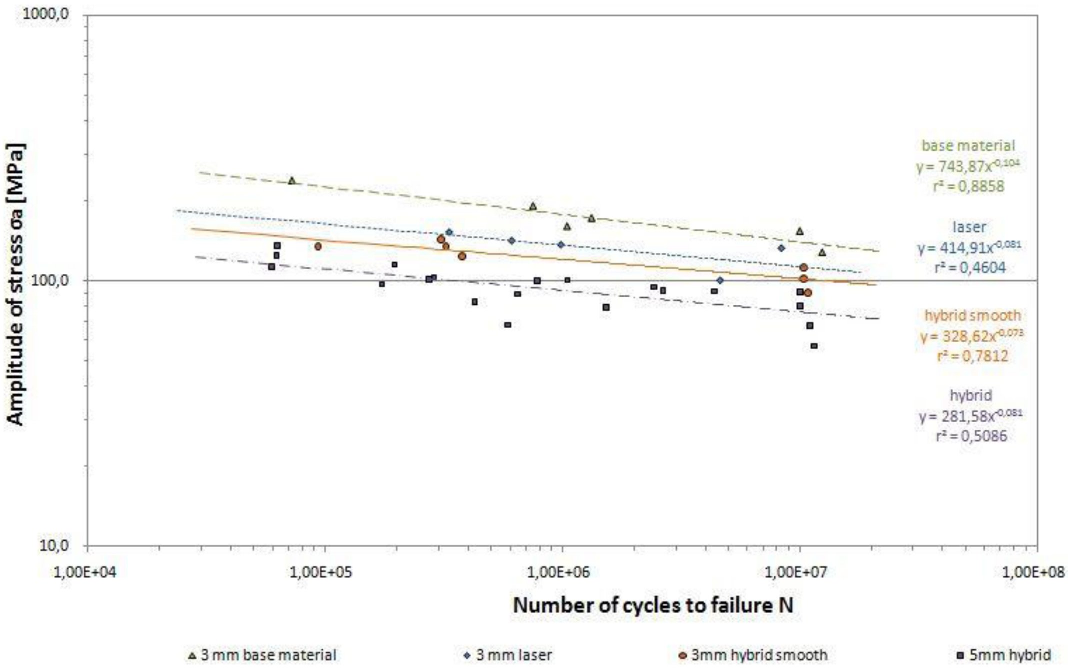

Figure 5. Ti gr 5, comparison between hybrid, laser, hybrid smoothed and base material.
Slika 5. Ti gr 5, poređenje između hibridnog, laserskog, hibridnog glatkog i osnovnog materijala

Table 2. Values of c_r.
Tabela 2. Vrednosti c_r

c_r ($5 \cdot 10^6$ cycles)		σ_I			
		base	laser	hybrid	hyb smooth
σ_{II}	base	1	0.80	0.54	0.71
	laser	1.26	1	0.68	0.90
	hybrid	1.85	1.47	1	1.32
	hyb smooth	1.40	1.12	0.76	1

The values refer to $N_f = 5 \cdot 10^6$. Other numbers of cycles are taken into account, but the very similar slopes of the curves confirm that the coefficient c_r, remains constant and nearly independent from the life cycles of the examined specimens.

It can be noted from the table that the smoothing operation increases the ratio with the base material, from 0.54 to 0.71, with an improvement over 30% of the fatigue strength of hybrid joints, thus reaching the behaviour of the hybrid joints near to the laser ones, with $c_r = 0.9$.

So interesting may be the idea that the differences between the two kinds of welding processes have an important role in the dimensions of the cord obtained, in the quality of the welding operation and in the number of defects generated, that results to be more critical for hybrid welding, but if all of the parameters are well controlled, and both welding operations are perfectly executed, after the smoothing operation of the hybrid cord, the fatigue resistance is approximately the same, reaching an infinite life duration with a local strain amplitude higher than 1000 μm/m, with a corresponding value of semi-amplitude of stress of about 107 MPa.

CONCLUSIONS

In this work hybrid welded titanium joints are studied. A preliminary brief comparison about the fatigue strength and the geometrical characteristics of the cord between laser welded joints and hybrid welded joints smoothed to the cord is done. Fatigue curves are plotted both in terms of local strain amplitude and nominal stress, comparing hybrid welded joints of Ti gr 5 with plate thickness of 5 mm and hybrid welded joints made of the same alloy, smoothed to the cord. In titanium hybrid welded joints, usually fracture starts from defects as slobbers of the cord or spots near to it, that result to be stress concentration points. These kinds of defects are eliminated through the smoothing operation, increasing in this way the fatigue strength. Nevertheless, internal porosities remain, and for both kinds of joints continue to be crack propagation locations.

The generation of fracture in the base metal for a smoothed joint and for laser welded joints, may be proof that, for the Ti gr 5 hybrid welded joints, the cord represents surely a geometrical discontinuity, but not a microstructural weak point, but further investigations, and the study of fracture surfaces with the help of a scanning electron microscope, are still necessary.

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Morozov Nikita, Academician of the Russian Academy of Sciences, Professor St.-Petersburg State University, Stary Peterhoff, Bibliotechnaja sq., 2, 198504, St.-Petersburg, Russia, Tel.: +7 (812) 428 69 89, e-mail: morozov@NM1016.spb.edu

Scientific Secretaries: Shlyannikov Valery, Professor Kazan Scientific Centre of the Russian Academy of Sciences Lobachevsky Street, 2/31, Kazan, 420111, Russia, Tel.: +7 (843) 231 90 20, e-mail: shlyannikov@mail.ru

Petrov Yury, Corresponding member of the Russian Academy of Sciences, Professor St.-Petersburg State University, Stary Peterhoff, Bibliotechnaja sq., 2, 198504, St.-Petersburg, Russia, Tel.: +7 (812) 323 29 54, e-mail: yp@YP1004.spb.edu

Matvienko Yury, Professor Mechanical Engineering Research Institute of Russian Academy of Sciences, 4 M.Kharitonievsky Per., 101990, Moscow, Russia, Tel.: +7 (499) 135 77 71, e-mail: matvienko7@yahoo.com