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SAFETY FACTORS ASSOCIATED WITH FATIGUE RESISTANCE OF TITANIUM HYBRID WELDED JOINTS

STEPENI SIGURNOSTI POVEZANI SA OTPORNOŠĆU PREMA ZAMORU KOD HIBRIDNIH ZAVARENIH SPOJEVA OD TITANA

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- titanium alloys
- laser and hybrid welding
- fatigue strength reduction factor

Ključne reči
- otpornost prema zamoru
- legure titana
- lasersko i hibridno zavarivanje
- faktor smanjenja zamorne čvrstoće

Abstract

This paper presents a detailed study on fatigue strength of welded joints made of two titanium alloys, grade 2 and grade 5, and welded by laser or hybrid process. Fatigue strength curves obtained for each alloy and each welding technique are compared in terms of safety factors with fatigue design curves of welded joints provided by standards.

Izvod

U ovom radu su predstavljena detaljna proučavanja zamorne čvrstoće zavarenih spojeva od dve legure titana, klase 2 i klase 5, zavarene laserskim ili hibridnim postupkom. Krive zamorne čvrstoće, dobijene za date legure i postupke zavarivanja, su upoređene s obzirom na stepene sigurnosti i prema standardnim krivama zamorne čvrstoće kod zavarenih spojeva.

INTRODUCTION

Welding of titanium is still considered a quite uncommon process because titanium alloys are utilized only in highly specialized engineering applications. Considerations on the lifetime costs of the structure make this material the preferred option in view of its unique mechanical properties. However, special care must be taken in executing the weld process because pure titanium and titanium alloys are highly susceptible to contamination from atmospheric gases. Shielding with inert gases may solve this problem but introduces complications in the technological process.

Gas-metal arc welding is used for joining parts of over 3 mm in thickness. The technological process, realised by means of pulsed current or in the spray mode, is less costly than gas-tungsten arc welding.

Laser beam welding is the most used technique for commercially pure titanium and titanium alloys. High energy beams are focused onto a very narrow area. This allows the welded and heat affected zones to be much smaller than for other welding processes and a more uniform thermal distribution is achieved. Consequently, high quality smooth welded joints without inclusions and distortions as well as lower residual stress can be realised. Laser welding technology entails more expensive equipment. Welding process parameters such as the laser beam power, welding speed and shielding gas purity govern the final geometry of the weld seam and joint quality.

Weldability of titanium alloys is in general good although the metal itself may be exposed to contamination during the welding process and during the subsequent cooling phase, till temperature decrease below 700°C. Fatigue strength of welded titanium alloy is lower that that of base metal because of microstructural modifications in the weld metal and heat affected zone, presence of residual stresses and eventual misalignment which introduces additional stresses. In order to account for these effects, design of welded structures against fatigue is not done on the basis of safety factors but by using fatigue design curves available in codes.

The aim of this paper is to study fatigue behaviour of two titanium alloys, grade 2 and grade 5, welded by laser or hybrid process. Fatigue strength curves are then compared with fatigue design curves for welded joints mainly in terms of safety factors.

MATERIAL AND WELDING PROCESS

Titanium grade 2 and titanium grade 5 (Ti-6Al-4V) /1/ welded joints are studied in this research. Titanium grade 2 has a hexagonal crystalline structure. Titanium grade 5 (Ti-6Al-4V) is a α–β alloy where aluminium is an α–stabilizing element and vanadium is a β–stabilizing element. Chemical composition of tested materials are reported in Tables 1 and 2, respectively.

In this study, static properties of welded joints are measured on specimens extracted from three different welded plates made of titanium grade 2 (1.5 mm thick) and titanium grade 5 (3 mm thick).

Stress-strain curves are obtained by recording strain values developed during the tensile test by means of electrical strain gauges bonded on both sides of each specimen. Mechanical properties (Young's modulus E, yield stress σ_Y, ultimate strength σ_u and elongation at fracture ε_f) obtained from experiments are summarized in Table 3. It can be noted that fracture strength of titanium alloy grade 5 is two times higher than that for titanium grade 2.

Table 1. Chemical composition of titanium grade 2.
Tabela 1. Hemijski sastav legure titana klase 2

Element	C	Fe	H	N	O
%	< 0.08	< 0.30	< 0.015	< 0.03	< 0.25

Table 2. Chemical composition of titanium grade 5.
Tabela 2. Hemijski sastav legure titana klase 5

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

Table 3. Mechanical properties of grade 2 and 5 titanium alloys.
Tabela 3. Mehaničke osobine legura titana klase 2 i 5

	E (MPa)	σ_y (MPa)	σ_u (MPa)	Elong. at fracture ε_f
Ti Gr 2	105.3	358.3	422.8	18%
Ti Gr 5	110.1	765.0	965.1	14%

WELDING PROCESS

Two joining processes are considered in this study: laser welding and hybrid laser-MIG welding. Characteristics of these welding processes are provided in Tables 4 and 5.

Table 4. Characteristics of the laser welding process.
Tabela 4. Karakteristike postupka zavarivanja laserom

Equipment	Laser ND-YAG -HAAS HL 2006D
Focal lens	f = 100 mm
Device for Gas for plasma suppression	standard nozzle f = 6 mm; special nozzle: Scarpeta TINEA
Gas for plasma suppression	He 4.8, delivery capacity 25 Nl/min
Shielding gas	Ar 5.0
Edge preparation	right (gap 0)
Power of laser beam	1600 W
Feed velocity	3000 mm/min

Table 5. Characteristics of hybrid (laser – MIG) welding process.
Tabela 5. Karakteristike hibridnog (laser–MIG) postupka

Laser CO_2 power	3000 W
MIG power	7200 W
Distance laser-MIG	0 mm
Welding velocity	2 m/min
Wire velocity	4 m/min
Gas for plasma suppression	He
Shielding gas	Ar

An important fact in laser welding is the narrow and deep configuration of the weld. This is due to the high energy concentration entailed by the process and the high welding speed that concurs to reduce heating of the specimen. The heat affected zone hence becomes narrow in laser welding thus involving less microstructural modification and lower residual stresses. In laser welding, a high power laser beam is focused on to the joint between two plates. Energy is very concentrated at one of the highest extent among the different welding processes currently available. Such a large concentration of thermal energy allows a weld with a high depth to width ratio and minimal thermal distortions to be obtained /2-3/.

In hybrid laser-arc welding a laser (CO_2 or Nd-YAG) is combined with an arc process (TIG, MIG, MAG or plasma). This makes it possible to benefit from the advantages of both processes. The laser beam allows deeper welds to be produced in just one pass, whereas the arc energy serves to increase welding speed and to fill the fit-up defects between the pieces to be joined. It was known for many years that combining a laser beam and an electric arc could produce welds with many of the technical advantages obtainable with a laser technique such as, for example, deep penetration and low distortion.

FATIGUE TESTS

Specimens submitted to tensile fatigue tests are obtained from titanium grade 2 and titanium grade 5 butt plates, welded by means of laser and hybrid techniques.

All fatigue tests are performed under load control (load ratio $R = 0.1$) on a 250 kN Schenck servo-hydraulic testing machine, with frequencies ranging between 10 and 15 Hz.

Fatigue final fracture path is localised in the base metal zone, away from the weld toe, for all laser welded joints and at the weld toe for hybrid ones.

The first series of fatigue tests is performed in order to compare fatigue resistance of titanium grade 2 and 5 alloys. Tests are carried out on rectangular plates of 1.5 mm thickness for titanium grade 2, and 3 mm for grade 5. All specimens have the same dimensions: 300 mm length and 40 mm width, and are laser welded. The second set of fatigue tests is performed in order to study the effects of different welding process on titanium grade 5. Finally, the third set of fatigue tests is executed on erased hybrid welded joint.

Influence of material on fatigue resistance of titanium alloy

Fatigue test results are plotted in fashion of stress range $\Delta\sigma$ versus the number of cycles to failure N_f (Fig. 1).

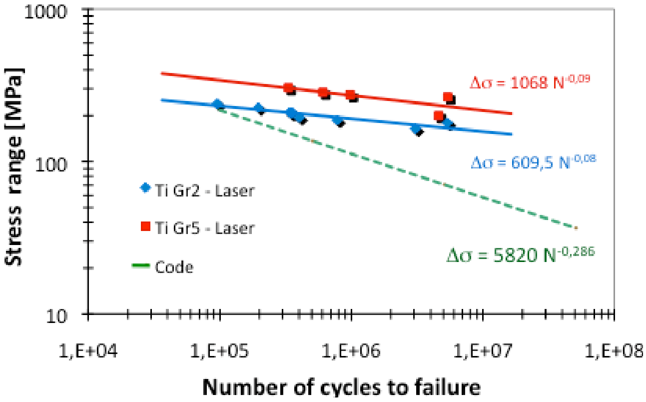

Figure 1. Fatigue resistance curves for laser welded grade 2 and grade 5 titanium alloys.
Slika 1. Krive otpornosti prema zamoru za laserski zavarene legure titana klase 2 i 5

Experimental data are fitted with a Basquin's type power law where the number of cycles to failure increases as a negative power function of the stress range $\Delta\sigma$:

$$\Delta\sigma = \sigma'_f \cdot (N_f)^b \quad (1)$$

In Eq. (1), σ'_f is fatigue strength and b the Basquin's exponent. These two parameters are reported in Table 6 together with the endurance limit σ_D conventionally defined at 2×10^6 cycles. It can be noted that the empirical rule used for steels, fatigue resistance equal to ultimate strength, is not satisfied. Values of Basquin's exponent are close to b = 0.1 as a common value.

Titanium grade 5 has higher fatigue resistance than titanium grade 2. In the $N_r = 10^3–10^7$ range for the same life duration, the ratio between applied stress ranges is in fact 1.40–1.20. However, the ratio of yield stress is 2.14. It should be considered that fatigue resistance of titanium alloys depends on the constitutive material. This aspect will be properly accounted for when experimental results are interpreted in view of fatigue design curves available in the standard that do not include any dependence on material. Figure 2 shows the fatigue curve according to AWS code /4/ and the two separate curves obtained for titanium grade 2 and 5 from experimental data.

Table 6. Fatigue resistance parameters of laser welded grade 2 and grade 5 titanium alloys.
Tabela 6. Parametri otpornosti prema zamoru laserski zavarenih legura titana klase 2 i 5

Material	σ'_f (MPa)	$-b$	σ_D (MPa) ($N = 5\times10^6$)
Grade 2	609.5	0.0840	167
Grade 5	1068	0.0991	232

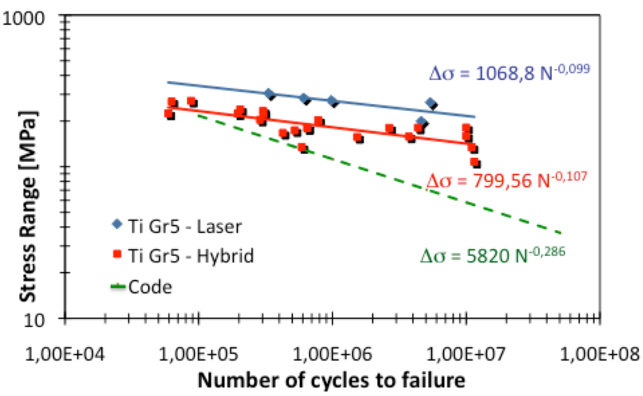

Figure 2. Fatigue resistance curves for laser and hybrid welded grade 5 titanium alloy.
Slika 2. Krive otpornosti prema zamoru za laserski u hibridno zavarenu leguru titana klase 5

Influence of welding process

The influence of welding process on fatigue strength is analysed only for the titanium grade 5 alloy by comparing results obtained for laser and hybrid laser-MIG specimens. Experimental results are presented in Fig. 2. A power law of Basquin's type is again utilized to fit data. Fatigue resistance, Basquin's exponent and the endurance limit are given in Table 7.

Fatigue resistance is higher in the case of laser welding. In fact, in $N_r = 10^3–10^7$ range, for the same life duration, the ratio of applied stress range is between 1.43 and 1.49. It should be considered that fatigue resistance of welded joint made in titanium alloy is also sensitive to welding process.

Table 7. Fatigue resistance parameters of laser and hybrid welded grade 5 titanium alloy.
Tabela 7. Parametri otpornosti prema zamoru laserski i hibridno zavarene legure titana klase 5

Welding	σ'_f (MPa)	$-b$	σ_D (MPa) ($N = 5\times10^6$)
Laser	1068	0.0991	232
Hybrid	799.5	0.1070	154

DESIGN OF WELDED JOINTS AGAINST FATIGUE

Welded joints (steel, aluminium and titanium alloys) are designed against fatigue by using basic fatigue design curves that statistically incorporate influence of residual stresses, stress ratio and safety factor. All fatigue design specifications present a series of S–N curves for particular weld details. Each curve is characterized by a detail category corresponding to the value of stress range at 2×10^6. All curves are parallel. The basic fatigue design S-N curves are expressed in the form:

$$\log_{10} N = \log_{10} K - m \cdot \log_{10} \Delta\sigma \quad (2)$$

where K is a fatigue resistance limit of the welded joint and m is the slope coefficient of the fatigue curve. For steel, basic fatigue design curves show two slopes. For shorter life, less than 10^7 cycles, a slope coefficient $m = 3$ is used. For longer fatigue life, a slope coefficient $m = 5$ is used until 10^8 cycles. For very long fatigue life, an endurance limit is expected. However, recent research work /5/ indicated continuous decrease in fatigue life in the so-called "endurance limit" regime or giga-cycle regime and propose to replace the endurance limit by a line with a slope coefficient $m = 45$ for steel and $m = 22$ for aluminium alloys.

Basic fatigue design curves of titanium alloys /4/ are similar but the slope coefficient is different $m = 3.5$. Furthermore, the endurance limit exists for long fatigue life, more than 5×10^6 cycles. The slightly higher slope observed for fatigue crack growth is confirmed in the welded joint fatigue testing /6/ and used to justify the change in slope. The modified slope implies that many weld configurations will have very similar design allowable stress ranges for both titanium and steel if the number of loading cycles is large: for example, more than 1 million cycles.

Structural Welding Code–Titanium includes a set of 14 original fatigue strength curves for different weld details. These fatigue curves are shown in Fig. 3 together with welded joint details.

In /6/, the fatigue strength curve for a butt joint made of titanium alloy (FAT3.5 class 80) is compared with experimental results provided by technical literature. Derivation of fatigue curves is illustrated in Fig. 4. All data found in literature are reported in one single graph.

A safety factor of 10 is then applied to life duration: this corresponds to a safety factor on stress range close to 2. These rounded values indicated that deterministic safety factors are used for that purpose.

The current trend in design codes is to use probabilistic safety factors associated to a given level of probability of fatigue failure. The safety factor is defined as the ratio between the mean stress value and the corresponding limit value for a given probability:

$$f_s = \frac{\sigma_a(Pr=0.5)}{\sigma_a(Pr=Pr^*)} \tag{3}$$

(a)

(b)

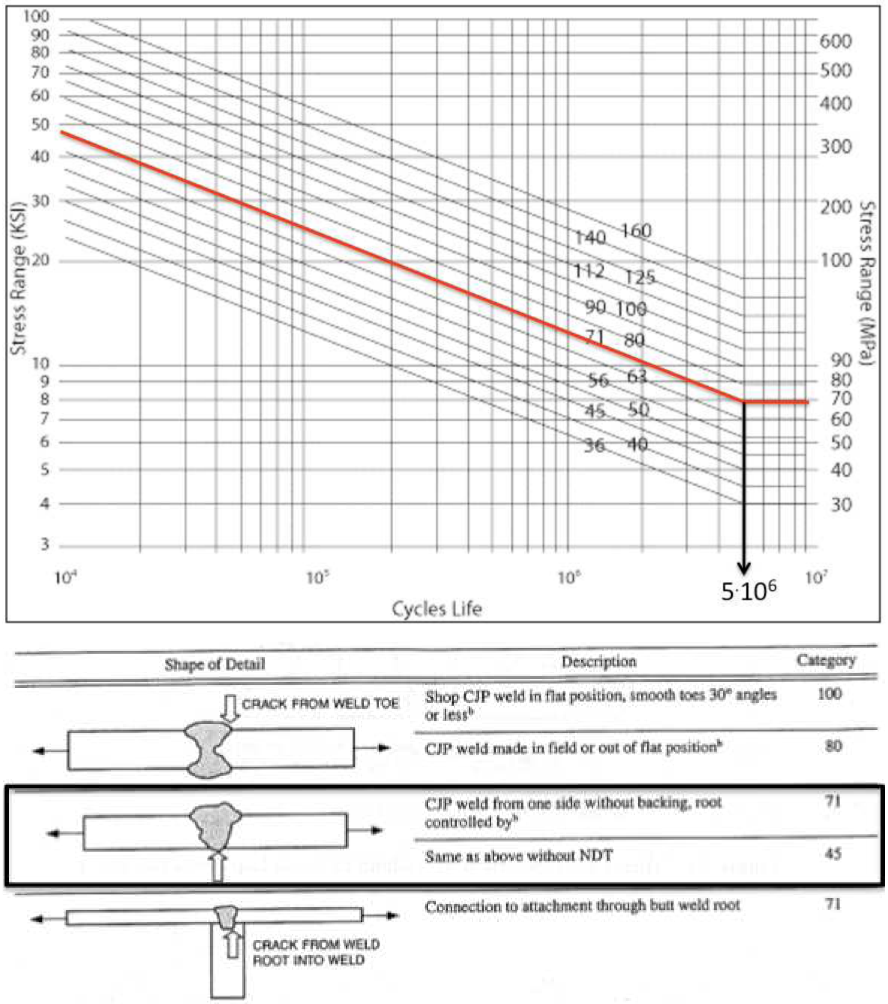

Figure 3. a) Fatigue strength curves for titanium welded joints from AWS D1.9 2007; b) detail categories for titanium alloys according to AWS D1.9 2007 (the detail of the present study is highlighted in the black frame).

Slika 3. a) Krive čvrstoće zamora za zavarene spojeve titana iz AWS D1.9 2007; b) detaljne kategorije legura titana prema AWS D1.9 2007 (detalj za ovaj rad je uokviren)

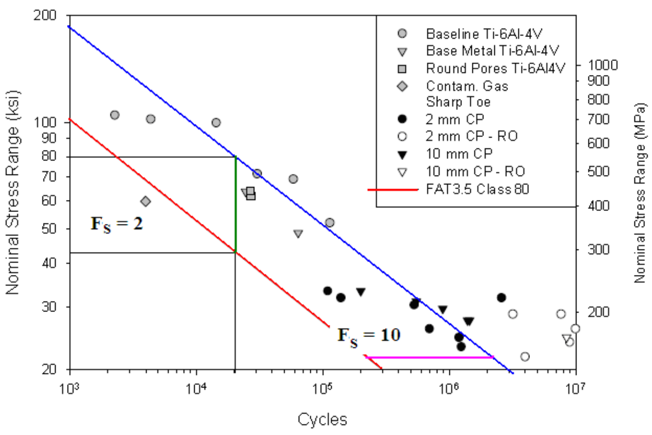

Figure 4. Derivation of fatigue design curves for welded titanium joints /6/.

Slika 4. Konstrukcija projektnih krivih zamora za zavarene spojeve titana /6/

However, this approach requires the knowledge of fatigue life duration distribution for a given stress range or the knowledge of stress range distribution for a given life duration. It is well known that for life duration less than 10^7 cycles and for a given stress range, distribution of number of cycles to failure is Log-normal or of the Weibull's type. For a given life duration, the distribution of stress range is instead Normal.

In many codes, the design curve is defined as corresponding to 2.3% probability of failure. This is equivalent to 2 standard deviations of $\log_{10}N$ below the mean S–N curve if fatigue endurance is log-normally distributed. This corresponds to an approximate safety factor on fatigue life of about 3.

The function of probability density for the Weibull distribution can be expressed as:

$$p(x) = cmx^{m-1}\exp(-cx^m) \tag{4}$$

where m is the Weibull modulus and c the normalisation factor. Mean value and standard deviation are respectively:

$$\overline{x} = c^{-1/m}\Gamma(1+1/m)$$
$$s_x^2 = c^{-2/m}\left[\Gamma(1+2/m) - \Gamma^2(1+1/m)\right] \quad (5)$$

The coefficient of variation is:

$$c_{V,x} = \sqrt{\frac{\Gamma(1+2/m)}{\Gamma^2(1+1/m)-1}} \quad (6)$$

where G is the Gamma-Euler function. Weibull's modulus can be estimated from the following empirical relationship:

$$m = c_{V,x}^{-1.09} \quad (7)$$

Various values for the coefficient of variation are indicated in literature. British Defence standards cite a value of 0.11 for aircraft grade aluminium alloys /7/. This value is intended to incorporate data scattering related to material and manufacturing variations. Forgues /8/ proposed a value of 0.0992 based on the analysis of 2451 fatigue tests on three aircraft grade alloys (Al7075, Al2024 and Al7475). Data for titanium alloys are not available but a good estimate can be made by assuming $c_{V,x} = 0.1$.

Then, for a given probability of failure, the safety factor is given by:

$$f_s = \frac{\Gamma(1+1/m)}{\left[\mathrm{Ln}(1/P_s^*)\right]^{1/m}} \quad (8)$$

For the butt joint class 71, the fatigue strength curve is described by the following equation:

$$\Delta\sigma = \Delta\sigma_f' \cdot (N_r)^{1/3.5} \quad (9)$$

where $\Delta\sigma_f'$ is the design fatigue resistance: $\Delta\sigma_f'$ = 71 MPa (for 5×10^6 cycles, the stress range is equal to 71 MPa).

From experimental and code curves, two safety factors are obtained:

- the safety factor on stress range $f_{s,\Delta\sigma}$

$$f_{s,\Delta\sigma} = \Delta\sigma_{exp}(N_r) / \Delta\sigma_{code}(N_r) \quad (10)$$

where $\Delta\sigma_{exp}$ and $\Delta\sigma_{code}$ are respectively the stress range relative to experimental results and that indicated in the design fatigue curve for the same number of cycles to failure;

- the safety factor on fatigue life $f_{s,Nr}$

$$f_{s,Nr} = N_{r,exp}(\Delta\sigma) / N_{r,code}(\Delta\sigma) \quad (11)$$

where $N_{r,exp}$ and $N_{r,code}$ are respectively the number of cycles for the stress range relative to experimental results and that indicated in the design fatigue curve for the same stress range.

Safety factors on stress range are listed in Table 8 and plotted in Fig. 5 for laser welded titanium grade 2 and 5 joints and hybrid welded titanium grade 5 joints. The following facts have been observed:

– safety factors never are constant and become larger as life duration increases. The fact that for life durations over 5×10^6 cycles endurance limit is expected from the Fat 3.5 Class 71 (71 MPa) has been taken into account.
– safety factors depend on material and are higher for laser welded titanium grade 5;
– for short life durations, safety factor is below the value of 2 indicated by the AWS D 1.9 2007 code.

Table 8. Safety factor on stress range for laser welded titanium grade 2 and 5 and for hybrid welded titanium grade 5.
Tabela 8. Stepen sigurnosti za raspon napona kod laserskih spojeva legura titana klase 2 i 5 i za hibridne spojeve titana klase 5

N_r	$f_{s,\Delta\sigma}$ Gr2 – Laser	$f_{s,\Delta\sigma}$ Gr 5 – Laser	$f_{s,\Delta\sigma}$ GR5 – HYBRID
10^5	1.12	1.75	1.08
10^6	1.80	2.74	1.62
2×10^6	2.07	3.14	1.84
5×10^6	2.50	3.76	2.16

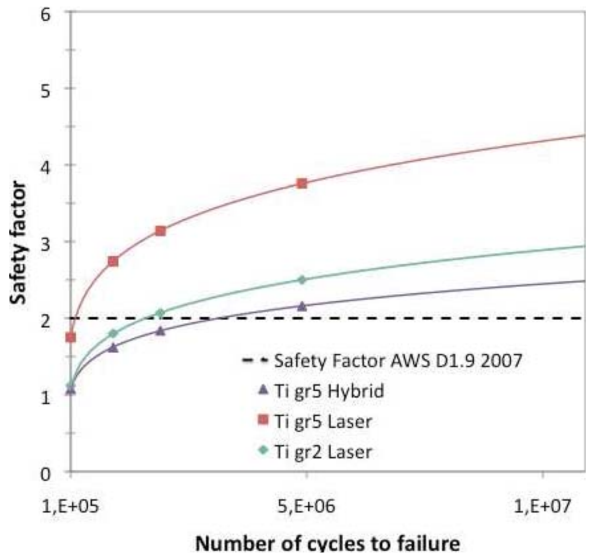

Figure 5. Safety factors for laser welded titanium grade 2 and 5 and for hybrid welded titanium grade 5 joints.
Slika 5. Stepeni sigurnosti za laserski spoj titana klase 2 i 5 i za hibridni spoj titana klase 5

Probability of failure associated with the safety factor values computed above is evaluated by means of Eq. (8). The corresponding data are shown in Table 9. It can be seen that for long life durations the probability of failure is extremely low and ranges below the conventional value of 10^{-6} used for assessing risks of human life. This probability is obtained for a safety factor of 2.95.

Table 9. Probability of failure for laser welded titanium grade 2 and 5 and for hybrid welded titanium grade 5.
Tabela 9. Verovatnoća loma laserskog spoja titana klase 2 i 5 i za hibridni spoj titana klase 5

N_r	P_f Gr 2 – Laser	P_f Gr 5 – Laser	P_f GR 5 – HYBRID
10^5	1.19×10^{-2}	1.01×10^{-4}	1.09×10^{-2}
10^6	4.03×10^{-5}	5.23×10^{-7}	7.11×10^{-5}
2×10^6	7.26×10^{-6}	1.07×10^{-7}	1.56×10^{-5}
5×10^6	2.93×10^{-7}	1.99×10^{-8}	6.35×10^{-7}

Table 10. Comparison of fatigue safety factor on life duration ($\Delta\sigma$ = 167 MPa).
Tabela 10. Poređenje stepena sigurnosti na zamor za vek trajanja ($\Delta\sigma$ = 167 MPa)

	Fat 3.5 Class 71	Ti grade 2	Ti grade 5
N_r	10^5	15×10^6	40×10^7
$f_{s,\Delta\sigma}$	2	150	4000

For a safety factor of 2, the probability of failure is 1.2×10^{-4}.

The safety factor on life duration is more difficult to evaluate because the Basquin's exponent of material is strongly different from those indicated in the Fat3.5 Class 71 design fatigue curve and fatigue curve is limited to 5×10^{6} cycles by the assumption that an endurance limit exists. However, comparisons can be made for the stress range of 167 MPa corresponding to 10^{5} cycles on the Fat 3.5 Class 71 fatigue design curve. Those data are listed in Table 10. It appears that the safety factor provided by the design fatigue curve Fat 3.5 Class 71 is close to 2 for short life duration (10^{5} cycles) but highly conservative for long fatigue life.

CONCLUSION

Fatigue resistance of titanium welded joints can be assessed by using the Basquin's law. The parameter of this law, namely the fatigue resistance and Basquin's exponent, depends on the titanium alloy type (grade 2 and grade 5) and the welding process (laser and hybrid laser-MIG). Structural titanium welding code includes a set of fatigue strength curves for different weld details that do not account for the type of alloy and the welding process. This limitation is clearly highlighted by the experimental results presented in this paper.

The mean value of Basquin's exponent for welded titanium alloy is about 0.09. In the code, a value of 0.285 (1/3.5) is used instead. This important difference leads to have highly conservative predictions in the design of titanium welded joint within the range of fatigue endurance characterised by safety factors greater than 2.

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