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Effect of elevated temperature and welding on low cycle fatigue strength of titanium alloys

H. Medekshas
Kaunas University of Technology, Kęstučio str.27, 44312 Kaunas, Lithuania, E-mail: henmed@ktu.lt

1. Introduction

The application of titanium-based alloys is continuously expanding due to their positive features such as low specific weight, high corrosion resistance and high strength and toughness. These alloys are used in aircraft engines, gas turbines and compressors blades, pressure vessels and other failure critical components, as well as surgical implants.

As some parts made of titanium alloys have to withstand low cycle fatigue, for instance near stress concentrations, the cyclic stress-strain behaviour and low cycle fatigue resistance of these alloys is a design concern.

Nevertheless, fatigue behaviour of titanium alloys is complicated by environmental sensitivity, internal hydrogen, contributing to localized embrittlement, microstructure and other factors, leading to crack growth anomalies. One of such undesirable features is titanium alloys sensitivity to some factors inevitable in parts production technological processes. Welding may be attributed to such factors. Some titanium alloys have favorable weld characteristics [1]; therefore welding is widely used in part production from titanium alloys processes. Welding of titanium alloys usually is performed in protective gas atmosphere, but, in spite of this, the heat effect on the alloy's microstructure is common. Welding can adversely affect the strength, toughness and fatigue properties of titanium alloys because of severe thermal cycles. Highenergy shock during welding causes appreciable beta grain growth in the heat affected zone (HAZ) adjacent to the weld fusion plane. Lynch et al. [2] investigated commercial aircraft and discovered that fatigue cracking had occurred in the HAZ in the aircraft duct manufactured from commercially pure titanium sheet. Jinkeun et al. [3] obtained that high cycle fatigue strength of the Ti-6Al-4V alloy weld was lower than that of the base metal, because of the presence of large micropores formed during welding, although it had the highest yield strength. Residual stresses in the HAZ play a key role in the crack growth, and they produce large effect on the near-threshold fatigue crack growth in the weld [4].

Great majority of the above mentioned phenomena can be faced in low cycle fatigue, and they can influence fatigue behaviour of an alloy. Unfortunately, in the literature sources there is scarce data relating low cycle fatigue strength and cyclic stress-strain behaviour of titanium alloys, especially welded ones, contrary to great amount of investigations related to fatigue crack growth and fracture analysis.

The objective of the present study is to analyze cyclic strength and stress-strain behaviour of as-supplied and welded titanium alloys subjected to low cycle loading at various temperatures.

2. Experimental procedure and materials

Two titanium alloys, namely, Ti-2.5Al-2Zr -α alloy and Ti-3.5Al-2V hardening pseudo-α alloy were selected for the tests. The Ti-2.5Al-2Zr -α alloy has no alloying elements in the composition and only the α phase in the microstructure. In the composition of Ti-3.5Al-2V pseudo-α alloy there are not only α stabilizers but also β stabilizers in an amount a little exceeding the certain limit of its solubility in the α phase; the microstructure of the alloy consists of α phase and a small amount of β phase. Mechanical characteristics of the materials are presented in the Table.

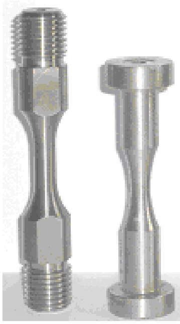
Table

Mechanical characteristics of the tested materials at various test temperatures

Material	Test temperature, °C	Yield strength, MPa	Ultimate tensile strength, MPa	Reduction of cros-section area, %
Ti-2.5Al-2Zr: as-supplied	20 350	496 296	552 483	44 71
HAZ	20 350	442 227	539 288	42 66
Weld	20 350	458 240	543 298	40 68
Ti-3.5AL-2V: as-supplied	20 350	669 372	733 474	31 50
HAZ	20 350	686 392	747 437	27 52
Weld	20 350	542 272	607 330	32 71

Smooth cylindrical round cross-section 10 mm diameter specimens were used in the investigation of as-supplied material. Tests of the welded joints were carried out on corset type specimens (Fig. 1, b). The weld was located in the narrowest part of the specimen. Strain controlled tests were carried out on the mechanical closed loop control testing machines. Loading frequency was 5-8 cycles per minute, depending on the strain range. The X-Y recorder registered cyclic stress-strain curves. Longitudinal strain of the cylindrical specimens and diametric strain of corset type specimens were measured. The total axial strain was computed from the diametric strain recorded in cyclic stress-strain experimental diagrams and used in the analysis.

Fatigue crack initiation (crack length 0.5-1 mm) and growth was fixed by the optical microscopy. Number of loading cycles to crack and to the final fracture was registered. Testing temperatures were chosen from the interval of temperatures mainly faced in operation of titanium alloys components, namely 20°C, 200°C and 350°C, but some tests, aimed at obtaining more reliable results, were carried out at other additional temperatures.



a b

Fig. 1 Specimens used in the investigation: a - cylindrical, b - corset type

Temperature was measured by platinum to platinum-rhodium thermocouple attached to the specimen by single-spot welding. Induction heating of the specimens, enabling convenient observation of fatigue crack initiation and growth, was used. Temperature gradient along the deformable part (20 mm) of a specimen did not exceed 2% of nominal value. Weld in the specimens was made by manual electric arc welding in argon protective atmosphere. Heat affected zone was induced by special heat treatment.

3. Stress-strain behaviour

Tensile properties of the investigated alloys both at room and elevated temperatures are presented in Table. It might be seen that there is marked effect of test temperature on tensile characteristics. There is appreciable increase in ductility parameters, i.e. elongation and reduction in area. This increase is characteristic for all tested materials and for all material conditions: as-supplied material, welded joints and heat affected zone. The degree of work hardening increased with the increase in temperature, and for all test conditions (weld, HAZ, as-supplied material) it has been higher than at room temperature. Comparison of the as-supplied material tensile characteristics with those of welded material and HAZ shows that for Ti-2.5Al-2Zr alloy the base material has higher ultimate tensile and yield strength, and higher plasticity characteristics than weld and HAZ material. The same property is noted for Ti-3.5AL-2V alloy weld, but material in the HAZ has higher strength and lower plasticity characteristics than the base material.

Cyclic stress-strain behaviour of these alloys had been investigated at stress and strain cycling. In this paper experimental data obtained at strain controlled cycling only are presented. Data related to stress controlled cycling of these alloys may be found in our previous publications [5, 6].

Cyclic stress-strain behaviour of Ti-3.5Al-2V alloy is represented by test data shown in Figs. 2 and 3. Fig. 2 shows the change of cyclic tension (bright dots) and compression (dark dots) stress amplitudes in course of strain controlled cycling of as-supplied material specimens. The specimens are loaded by approximately the same strain range (0.90-0.95)% at 20°C, 200°C, 350°C and 450°C temperatures. For comparison, one specimen, cycled at 4.4% strain amplitude, is presented in the Fig. 2 Analysis of cyclic stress-strain curves showed that for Ti-3.5Al-2V alloy in general constant stress value was obtained in course of strain controlled cyclic loading. This alloy preserves cyclic stability at all strain ranges in the interval from 0.5 to 10.4 percents, and all temperatures from 20°C to 450°C. Cyclic stability of this alloy is noted at stress controlled cycling as well [5, 6, 7]. Fatigue crack initiation and growth causes reduction of tension and compression stress amplitudes, which is represented by falling down sections of the curves. Rapid drop in stress amplitudes before fracture is associated with a stable crack propagation stage [8]. This stage is shown in Fig. 2 only: in the subsequent Figs. 3, 4 and 5 this stage is omitted.

Different values of tension and compression stress amplitudes in a cycle are observed, and this phenomenon is explained by both loading conditions (in tension cross-sectional area of the specimen decreases, in compression – increases), and materials anisotropy (different resistance to tension and compression). Similar behaviour is observed in testing other titanium alloys and steels. Some authors [9, 10, 11] explain this fact by local cracking appearing already in the first stress-strain cycle and leading to reduction of the stress in tension but not in compression semicycles.

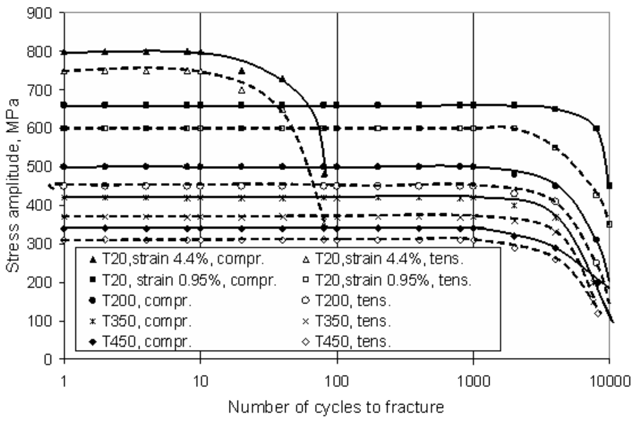


Fig. 2 Tension and compression stress amplitude versus number of loading semicycles for Ti-3.5Al-2V alloy specimens tested at various temperatures

It should be noted that fatigue crack growth takes place during great majority of the loading cycles. For the specimens tested at strain amplitude 0.9%, crack used to initiate at <2000 cycles and the specimens used to fracture at 8 000-10 000 cycles.

Ti-3.5Al-2V alloy specimens with induced HAZ (Fig. 3), tested at various strain ranges and temperatures, demonstrated some cyclic softening at high strain ranges (1.48% and more), and cyclic stability at lower strain ranges. The figure shows numbers of cycles to crack initiation only; crack growth is not shown. Such behaviour is attributed to all test temperatures.

Specimens with the weld of this alloy demonstrated similar to the specimens with HAZ behaviour at all tested temperatures (20°C, 200°C and 350°C) and strain ranges.

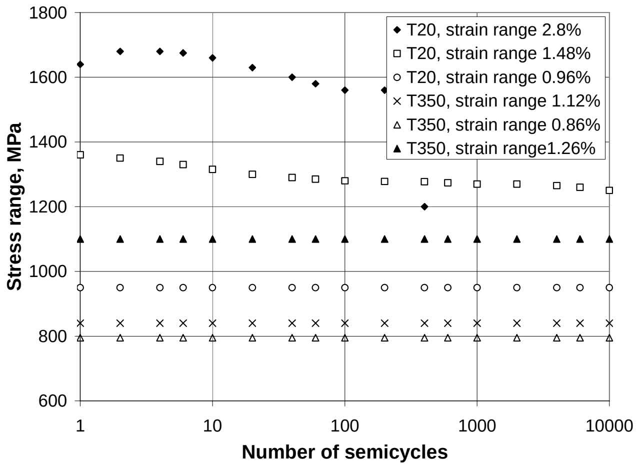


Fig. 3 Stress range versus number of semi cycles for Ti-3.5Al-2V alloy specimens with HAZ tested at various strain ranges at 20°C and 350°C temperatures

Ti-2.5Al-2Zr -α alloy in as supplied conditions at room temperature demonstrated cyclic stability at all strain ranges. At elevated 200°C and 350°C temperatures this alloy preserved cyclic stability at small strain ranges (<1.25%) only. At higher strain ranges this stability changes to cyclic hardening, which is more intensive at greater strain ranges and higher temperatures

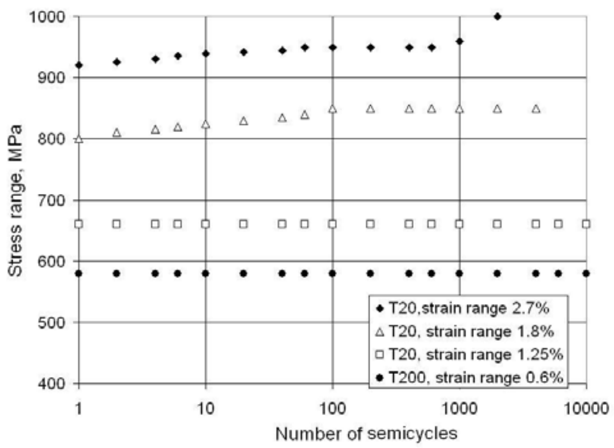


Fig. 4 Stress range versus number of loading semicycles for Ti-2.5Al-2Zr alloy specimens with induced HAZ, tested at various strain ranges and temperatures

Heat affected zone a little intensified cyclic hardening process, retaining the same main trend (Fig. 4). Welded specimens (Fig. 5) retained cyclic hardening property at strain ranges $\geq 0.75\%$; at lower strain ranges stabilized stresses were obtained. Such behaviour was observed at all test temperatures.

4. Cyclic strength of the alloys

Aiming to compare low cycle fatigue strength of the parent material with the strength of specimens containing weld or heat affected zone low cycle fatigue tests of as-supplied materials were carried out. The specimens from as-supplied Ti-3.5Al-2V and Ti-2.5Al–2Zr alloys were made and tested at room temperature. Testing of these specimens data was approximated by the power trendlines shown in Fig. 6.

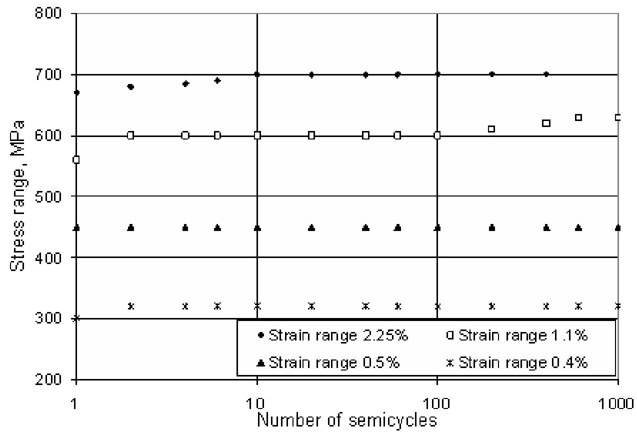


Fig. 5 Stress range versus number of loading semicycles for Ti-2.5Al-2Zr alloy specimens with the weld, tested at various strain ranges at 350°C temperature

Usually the relationship between total strain range and the number of cycles is approximated by a curve in logarithmic coordinates, but in our tests, due to comparatively small test basis, where plastic strain predetermines fracture, it was possible the experimental data of both alloys to approximate by the separate straight lines of different slope. These lines were used for comparisons. Fig. 6 shows that at total strain ranges exceeding 0.8% Ti-2.5Al–2Zr alloy has higher lifetime than Ti-3.5Al-2V alloy.

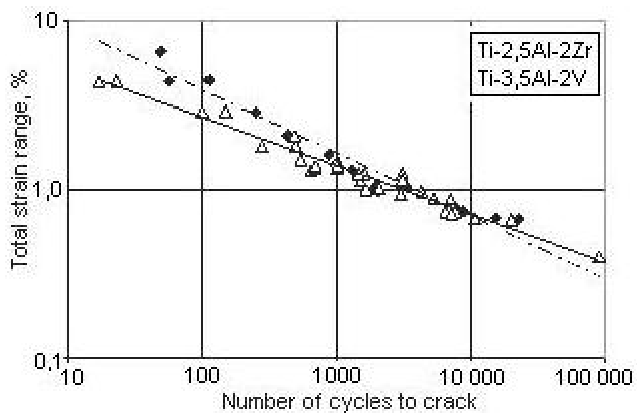


Fig. 6 Total strain range versus number of cycles to crack for as-supplied Ti - 2.5Al – 2Zr and Ti-3.5Al-2V alloys specimens tested at room temperature

Temperature effect on low cycle fatigue properties is show in Fig. 7, where experimental points corresponding to the number of cycles to fracture of Ti-2.5Al–2Zr alloy specimens in as- supplied conditions tested at room and 350°C temperatures are presented.

The data show that test temperature in the investigated interval has negligible effect on the number of cycles. For Ti-3.5Al-2V alloy specimens some increase of the number of cycles at elevated temperature in comparison with that at room temperature was noticed.

Fatigue tests data of Ti- 3.5Al-2V alloy welds are presented in Figs. 8 and 9. Fig. 8 shows that at room temperature specimens with the weld (points) failed at the same approximately number of cycles as those made of as-supplied material (line).

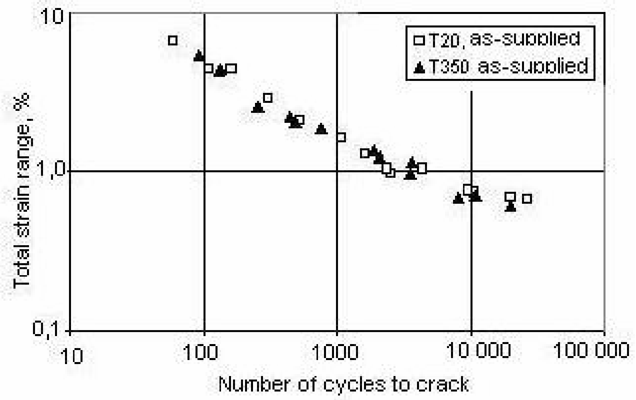


Fig. 7 Strain controlled fatigue data for Ti-2.5Al–2Zr alloy specimens tested at room and 350°C temperatures

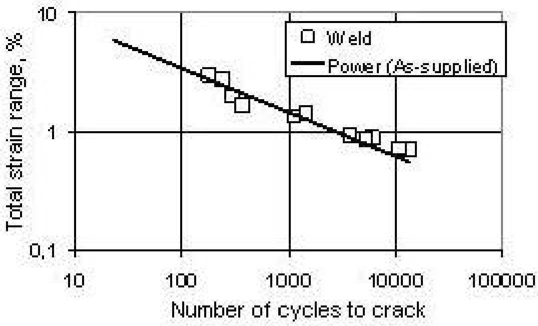


Fig. 8 Comparison of low cycle fatigue strength of as - supplied and with the weld Ti-3.5Al-2V alloy specimens tested at room temperature

Fig. 9 shows strain cycling fatigue of the welded specimens data obtained at 20°C, 200°C and 350°C temperatures. At strain ranges $\varepsilon \leq 1.2\%$ the highest number of cycles to fracture is obtained at room temperature, the lowest – at 350°C temperature, and the points for 200°C are in the middle. Thus, the curves intersect at the point, corresponding to approximately $N_c \approx 1000$ cycles. It might be concluded that at small strain ranges ($\varepsilon \leq 1.2\%$) temperature decreases lifetime of the welded joints, but at high strain ranges, the temperature increases lifetime of the welds. Comparison of the welded specimens test data with as-supplied material test data presented in Fig. 8 allows to draw conclusion that specimens with the weld withstand approximately the same number of cycles to crack as the specimens made from as-supplied material. This feature is characteristic for 20°C, 200°C and 350°C temperatures.

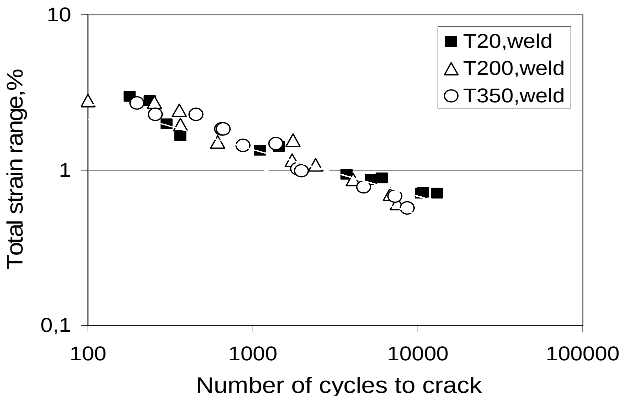


Fig. 9 Total strain range versus number of cycles to crack for Ti-3.5Al-2V alloy specimens with the weld tested at 20°C, 200°C and 350°C temperatures

Welded joints of the Ti-2.5Al-2Zr α-alloy were tested at 20°C and 350°C temperatures. Experimental data obtained in tests at 350°C temperature are presented in Fig. 10, where, for comparison, points for as-supplied alloy are shown as well. Fig. 10 shows that for welded specimens, the number of cycles to crack at 350°C temperature is more than ten times reduced in comparison with that of as-supplied material at room temperature.

For welded specimens tested at room temperature reduced durability (not shown in Fig. 10) in comparison with as-supplied material is obtained as well, but this reduction is smaller than that for the welds tested at 350°C temperature.

Thus, it is worth to notice, that welded specimens of the Ti-2.5Al-2Zr alloy, contrary to the as- supplied alloy specimens (see Fig. 7), have demonstrated temperature sensitivity.

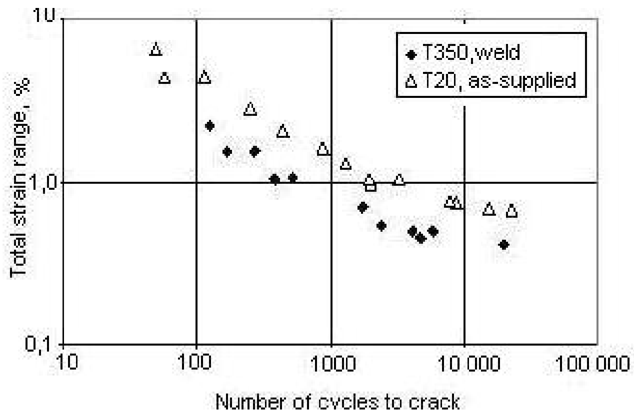


Fig. 10 Number of cycles to crack for Ti-2.5Al-2Zr α-alloy specimens with the weld and specimens in as-supplied conditions tested at 20°C and 350°C temperatures correspondingly

Reduced durability and increased scatter of the experimental points obtained in the welded specimens tests, is the result of macrostructure and microstructure changes during the welding process**.** One of the welding process factors influencing materials properties is heat. A specimen zone adjacent to the weld is called heat affected zone, because material properties in this zone are changed due to heat treatment resulting from rise of the temperature due to the heat, coming from the weld, and cooling due to the heat flow into environment.

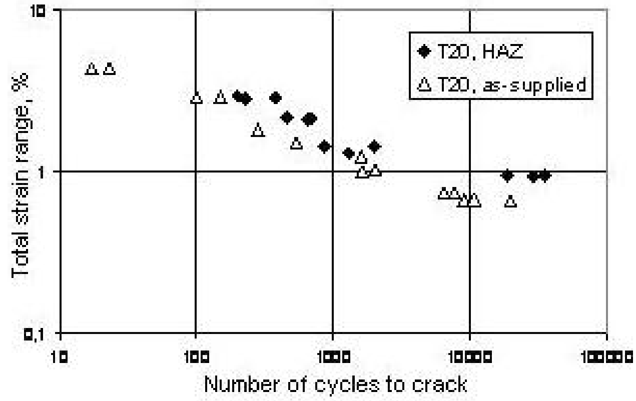


Fig. 11 Durability comparison for Ti-3.5Al-2V alloy specimens with HAZ and specimens machined from as-supplied material tested at room temperature

Two parties of the specimens with heat affected zone (HAZ) were tested. Test data were compared with the data obtained on as-supplied material specimens. Fig. 11 shows the plot of total strain range versus number of cycles to crack forTi-3.5Al-2V alloy specimens with HAZ and specimens machined from as-supplied material tested at room temperature.

It should be noted that heat affected zone has no damaging effect on this alloy; in contrary, specimens with HAZ showed longer lifetime than those in as-supplied conditions. The effect of HAZ on low cycle fatigue properties of Ti-2.5Al-2Zr alloy specimens is similar in comparison to that obtained for Ti-3.5Al-2V alloy.

Generalizing test data of the specimens with heat affected zone, it may be concluded that for both tested alloys the HAZ has no detrimental effect on the number of cycles to crack

5. Verification of the design Code

Although in low cycle fatigue studies the experimental data are commonly analyzed in terms of strain, the data representation more convenient to a designer is one which shows stress versus cycles. The use of stress as a variable makes it possible to show low cycle fatigue data as conventional S-N curves.

Experimental data obtained in testing 3.5Al-2V alloy specimens were approximated according to the Code [12] requirements. The Code is developed for steels; therefore it has a sense to check it's applicability to titanium alloys.

At strain controlled cycling fatigue fracture takes place, therefore, fatigue fracture criterion was applied. Low cycle fatigue design curves were calculated from the following relationships, corresponding to fatigue fracture criterion

$$\sigma_a^* = \frac{2.3E^t}{n_\sigma\left(4\left[N\right]^m + \frac{1+r^*}{1-r^*}\right)} lg\frac{100}{100-\psi^t} + \frac{\sigma_{-1}^t}{n_\sigma\left(1+\frac{\sigma_{-1}^t}{\sigma_u^t}\frac{1+r^*}{1-r^*}\right)} \quad (1)$$

$$\sigma_a^* = \frac{2.3E^t}{4\left(n_N\left[N\right]^m + \frac{1+r^*}{1-r^*}\right)} lg\frac{100}{100-\psi^t} + \frac{\sigma_{-1}^t}{1+\frac{\sigma_{-1}^t}{\sigma_u^t}\frac{1+r^*}{1-r^*}} \quad (2)$$

where σ_a^* is conditional (fictive) allowable elastic stress amplitude; E^t is modulus of elasticity at certain temperature *T*; n_σ is stress safety factor; n_N is number of cycles safety factor; $\left[N\right]$ is allowable number of cycles; *r** is conditional stress ratio; σ_{-1}^t and σ_u^t are fatigue limit stress and ultimate tensile stress correspondingly at certain temperature; ψ^t is reduction of cross-section area at certain temperature.

Parameters of the relationships (1) and (2) were calculated as follows.

Power *m* was calculated according to the formula

$$m = 0.36 + 2.10^{-3}\sigma_u^t . \quad (3)$$

Fatigue limit was calculated from the formula

$$\sigma_{-1}^t = \left(0.54 - 2.10^{-3}\sigma_u^t\right)\sigma_u^t \quad (4)$$

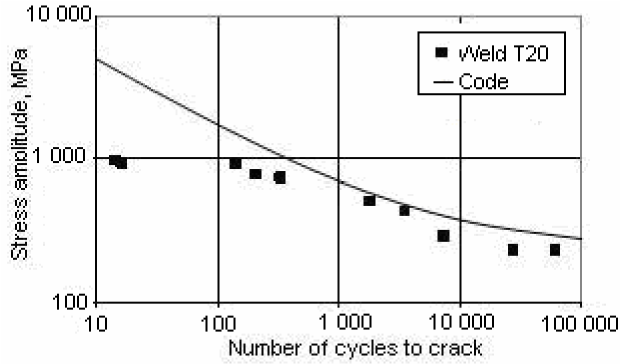


Fig. 12 The Code design curve in comparison with experimental data obtained in testing of Ti-2.5Al-2Zr alloy welded specimens

All the rest data are taken from the experiments.

Taking into account that tests were carried out at stress ratio $r = -1$, and assuming $n_\sigma = n_N = 1$, the following equation was obtained from the Code equations (1) and (2)

$$\sigma_a^* = \frac{2.3E^t}{4\left[N\right]^m} lg\frac{100}{100-\psi^t} + \sigma_{-1}^t \quad (5)$$

In Fig. 6 the design curves calculated according to Eq. (5) for the Ti-2.5Al-2Zr alloy welded specimens and experimental points are presented. The following monotonous tension at room temperature characteristics of the alloy weld were used in calculation**:** $\sigma_y^t = 458$ MPa, $\sigma_u^t = 543$ MPa, $\psi^t = 40\%$, $E^t = 1.12\ 10^5$ MPa.

The conditional stress σ_a^* for experimental points was calculated from the relationship

$$\sigma_a^* = eE^t \quad (6)$$

where *e* is total strain amplitude, measured from cyclic stress-strain curve.

Because it was assumed that safety factors $n_\sigma = n_N = 1$, the experimental points in Fig. 12 should be located on the Code curve. But the design curve in general badly approximates experimental data: it predicts higher than experiment does number of cycles to crack.

It means that necessary safety of a structure calculated according to this curve will not be ensured.

6. Conclusions

Low cycle fatigue tension-compression at constant strain range tests of Ti-3.5Al-2V titanium *pseudo* α-alloy and Ti-2.5Al-2Zr α-alloy specimens with welds showed different behaviour.

1. Welded specimens of Ti-3.5Al-2V titanium *pseudo* α-alloy survived similar number of cycles to crack as did the specimens made from as-supplied material. Such behaviour was observed at all test temperatures (20°C, 200°C, 350°C), but at higher temperatures some temperature effect on the number of cycles is noticeable.
2. The Ti-2.5Al-2Zr α-alloy specimens with the welds showed noticeably decreased number of cycles to crack in comparison with as-supplied material specimens. Welds of this alloy are sensitive to temperature: the lifetime at elevated temperatures is obtained shorter than that at room temperature.
3. For both tested alloys the number of cycles to crack for the specimens with induced heat affected zone is obtained higher than that for specimens machined from as-supplied material.
4. Design curves constructed according to Code badly approximate experimental data.

References

1. **Imam, M. A., Chu, H. P., Rath, B. B.** Fatigue properties of titanium alloy Ti-6Al-2Cb-1Ta-0.8Mo.-Materials Science and Engineering, A323. 2002, p.457-461.
2. **Lynch, S.P., Hole, S. and Timotins Passag.** Failures of welded titanium aircraft ducts.-Engineering Failure Analysis, 1995, 2(4), p.257-273.
3. **Jinkeun, O., Nack, J. Kim, Sunghak Lee, Eui W. Lee.** Correlation of fatigue properties and microstructure in investment cast Ti-6Al-4V welds.-Materials Science and Engineering, 2003, A340, p.232-242.
4. **John, R., Jata, K.V., Sadananda, K.** Residual stress effects on near-threshold fatigue crack growth in friction stir welds in aerospace alloys.-Int. J. of Fatigue, 2003, 25, p.938-948
5. **Medeksas, H.** Effect of mean stress and strain on low cycle fatigue strength of notched components. -Mechanika. -Kaunas: Technologija, 2004, Nr.6(50), p.30-35.
6. **Medekshas, H.** Environment effect on low cycle fatigue properties of titanium alloys.-J. Strain Analysis, 2006, 41, p.1-11.
7. **Medeksas, H., Balina, V.S.** Assessment of low cycle fatigue strength of notched components.-Mater Des 27, 2006, p.132-140.
8. **Gloanec, A.L., Jouiad, M., Bertheau, D., Grange, M., Hénaff, G.** Low-cycle fatigue and deformation substructures in an engineering TiAl alloy. -Intermetallics, 2007, v.15, Issue 4, p.520-531.
9. **Recina, V., Karlsson, B.** High temperature low cycle fatigue properties of Ti-48Al-2W-0.5Si gamma titanium aluminide.-Materials Science and Engineering, A, 1999, 262, (1-2), p.70-81.
10. **Vishniakas, I.** Study of metal structure welded on the titanium malleable alloy. -Mechanika. -Kaunas: Technologija, 2007, Nr.4(66), p.69-72.
11. **Krenevičius, A., Leonavičius, M., Petraitis, G., Gutauskas, M., Stonkus, R.** Strength of differently cooled cast iron subjected to cyclic loading. -Mechanika. -Kaunas: Technologija, 2007, Nr.4(66), p.18-22.
12. Strength evaluation code of structural elements of nuclear reactors, steam generators, vessels and pipelines of nuclear power stations, experimental and research nuclear reactors. Metallurgia, 1983 (in Russian).

H. Medekšas

TEMPERATŪROS IR SUVIRINIMO ĮTAKA TITANO LYDINIŲ MAŽACIKLIAM STIPRUMUI

Reziumė

Straipsnyje tiriama aukštų temperatūrų ir suvirinimo įtaka dviejų pramoninių titano lydinių mažacikliam stiprumui. Standaus mažaciklio tempimo-gniuždymo bandymai atlikti 20°C, 200°C ir 350°C temperatūrose. Naudoti bandiniai, pagaminti iš tiekimo būsenos medžiagos, ir bandiniai su suvirinimo siūle ir terminės įtakos zona. Padarytos išvados apie suvirinimo, terminės įtakos zonos ir temperatūros poveikį lydinių savybėms, veikiant mažaciklėms apkrovoms.

H. Medekshas

EFFECT OF ELEVATED TEMPERATURE AND WELDING ON LOW CYCLE FATIGUE STRENGTH OF TITANIUM ALLOYS

Summary

An attempt is made to evaluate effect of elevated temperature and welding process on low cycle fatigue properties of two titanium alloys. Strain controlled low cycle tension-compression tests were carried out at 20°C, 200°C and 350°C temperatures. Specimens machined from as- supplied material and those with the weld and heat affected zone were used. Conclusions relating the effect of weld, heat affected zone and test temperature on low cycle fatigue properties are made.

Г. Медекшас

ВЛИЯНИЕ ТЕМПЕРАТУРЫ И СВАРКИ НА МАЛОЦИКЛОВУЮ ПРОЧНОСТЬ ТИТАНОВЫХ СПЛАВОВ

Резюме

В работе приведены данные о влиянии повышенной температуры и сварного шва на малоцикловую прочность двух титановых сплавов. Жесткое растяжение – сжатие проводилось при 20°C, 200°C и 350°C температурах. Образцы изготавливали из сплавов в состоянии поставки, а также со сварным швом и зоной термического влияния. Сделаны выводы о влиянии на малоцикловую прочность повышенной температуры, сварного шва и зоны термического влияния.

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