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GROWTH AND DAMAGE OF THE α-STABILIZED LAYER IN THE TITANIUM ALLOY VT3-1 DURING THERMAL CYCLING

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The interaction between cyclic loading and the surrounding environment has to be taken into account especially at high temperature exposure. In atmospheric conditions fatigue and oxidation take place parallel. This results in a shorter crack initiatial period and enhanced crack propagation both in thermal cycling and isothermal conditions. In the present work, the development of α-stabilized layer in an α + β titanium alloy was investigated during high temperature thermal cycling in air environment. The constrained samples were cyclically heated between the lower temperature of 200 °C and the upper limit of 900, 1000 and 1100 °C, respectively. The oxygen containing α-phase nucleated on the lamellae of the α´ martensite when during the thermal cycling the maximum temperature exceeded the transformation temperature of the alloy. Maximum temperature and total exposure time showed to be decisive for the growth of the a layer stabilized by diffusion of the oxygen into the material. In the embrittlened diffusion layer cracks were initiated, growing inward exposing new surfaces for the diffusion of oxygen and development of α-layers leading to an accelerated damage process.

Key words: *α-stabilized layer, thermal cycling, thermal stresses*

Rast i oštećenje α-stabiliziranog sloja u slitini titanija VT3-1 tijekom toplinskog cikliranja. Interakcija između cikličkog opterećivanja i neposrednog okruženja se mora uzeti u obzir, naročito pri izlaganju visokim temperaturama. U atmosferskim uvjetima dešavaju se paralelno zamor i oksidacija. To dovodi do kraćeg vremenskog perioda i pospješuje širenje pukotina jednako tijekom termičkih cikliranja i tijekom izotermalnih uvjeta. U prikazanom radu se istraživao razvoj α-stabiliziranog sloja u slitini titanija α + β tijekom termičkog cikliranja pod visokom temperaturom u zračnom okruženju. Uzorci su ciklički zagrijavani između nižih temperatura od 200 °C i gornje granice od 900, 1000 i 1100 °C. Kisik koji sadrži α-fazu poticao je stvaranje klica na lamelama α´-martenzita, kad je tijekom termičkog cikliranja maksimalna temperatura prešla temperaturu transformacije slitine. Maksimalna temperatura i ukupno vrijeme izlaganja su se pokazale odlučujućim za rast sloja difuzijom kisika u materijal. U krhkom difuzijskom sloju nastaju pukotine koje se šire prema unutra stvarajući tako nove površine izložene difuziji kisika i razvoju α-slojeva što je dovodilo do ubrzanog procesa oštećivanja.

Ključne riječi: *α-stabilizirani sloj, termičko cikliranje, termičko naprezanje*

INTRODUCTION

The detrimental effect of oxidation on the damage in cyclic loading is well known. The result of the interaction of cyclic stresses and oxidation is a shorter crack initiatial period and enhanced crack propagation [1-3] both in isothermal low cycle fatigue and thermal fatigue. Most of the published data concern superalloys [3, 5], carbon and alloy steels [6], where the fatigue damage process acceleration is ascribed to enhanced oxidation kinetics [2] and surface oxide fracturing and spalling [2, 3].

The present work deals with the development of the a-stabilized layer in an α + β titanium alloy during high temperature thermal cycling. The obtained data may be useful in understanding the impact of oxygen embrittlement of the surface layer on the thermal fatigue damage.

MATERIAL AND EXPERIMENTS

The alloy used for thermal cycling was a two-phase α + β titanium alloy with the composition of Ti-6Al-2.5Mo-1.5Cr. The thermal cycling was conduced in a Zwick ten-

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sile machine with resistance heating as described in [7]. The loose samples were fixed firmly in the crossheads of the electronic tensile machine after heating them to the upper temperature of the thermal cycle (900, 1000, 1100 °C). The lower temperature was 200 °C. During the cooling period as a result of thermal contraction of the constrained samples mechanical stress was induced which, as Figure 1. shows, was in antiphase with the temperature cycle. For microstructural observations specimens were cut from the central part of the thermally cycled samples.

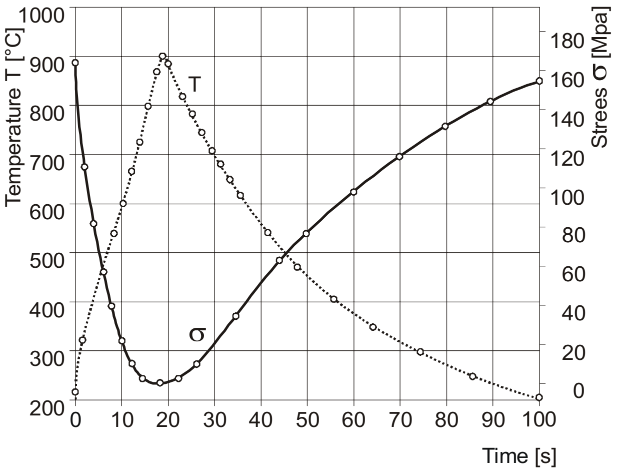

Figure 1. **Thermal and stress cycles in the sample cycled between 200 and 900 °C**

Slika 1. **Termički ciklusi i ciklusi naprezanja na uzorku cikliranom između 200 i 900 °C**

RESULTS AND DISCUSSION

The original microstructure prior to thermal cycling consisted of fine a particles embedded in the matrix of the transformed β phase, Figure 2.a. Thermal cycling resulted in micro structural changes both in the central area of the cylindrical specimens and in the surface region too. Crack formation was limited to the surface.

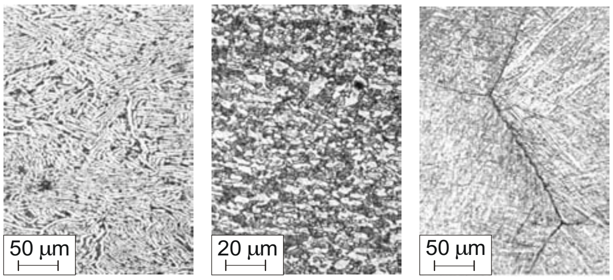

Figure 2. **a) The original microstructure of the Ti-6Al2.5Mo-1.5Cr alloy, b) microstructure after thermal cycling between 200 and 900 °C after 160 cycles, c) microstructure after thermal cycling between 200 and 1100 °C after 160 cycles**

Slika 2. **a) Polazna struktura slitine Ti-6Al2.5Mo-15Cr, b) mikrostruktura nakon 160 ciklusa termičkog cikliranja između 200 i 900 °C, c) mikrostruktura nakon 160 ciklusa termičkog cikliranja između 200 i 1100 °C**

Micro structural changes in the central area

The samples which were exposed to thermal cycles with the upper temperature 900 °C already showed some differences in their microstructure after thermal cycling in comparison to the original state. These changes could be resumed as a certain degree of globularisation of some of α lamellae, Figure 2.b.

At the relatively high cooling rates during the thermal cycling the α particles precipitated from the β phase in the form of fine β lamellae between the coarser original α globules. Both coarse and fine α particles are present therefore in the microstructure. When during the thermal cycling the maximum temperature exceeded the transformation temperature of the alloy (being this temperature in the range between 960 - 1000 °C) the final microstructure was α′-martensite with visible boundaries of the original β grains, Figure 3.c. Thickening of grain boundaries and α phase precipitation on grain boundaries were also observed but explicit grain boundary sliding was not registered.

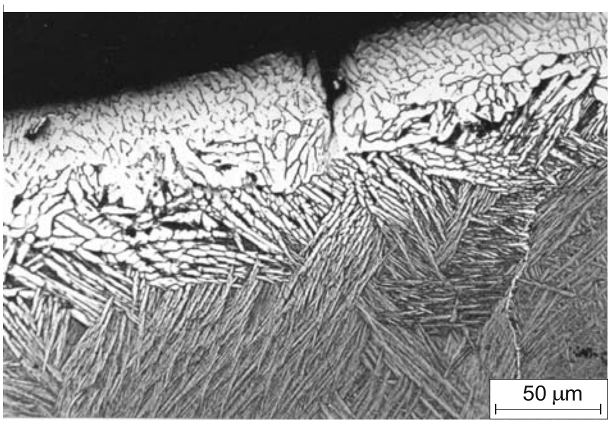

Figure 3. **Microstructure of the surface area of a sample cycled between 200 and 1100 °C (N = 100)**

Slika 3. **Mikrostrukture površine uzorka cikliranom na temperaturi između 200 i 1100 °C, (N = 100)**

Micro structural changes in the surface area

On the surface of Ti-Al alloys containing less than 50 % of aluminium intermixed TiO_2/Al_2O_3 scales are formed, while the titania act as a short-circuit transport path leading to interstitial dissolution of oxygen by diffusion into the alloy during the high-temperature exposure in air [8]. Figure 3. shows the surface region of a specimen cycled between 200 and 1100 °C. A distinct layer with white α particles can be observed on the micrograph. The dissolved oxygen in the α phase stabilizes these particles, therefore the denomination of α-stabilized layer. In a detailed view of the microstructure of the α-stabilized layer it is evident that the α-stabilized grains develop from the fine lamellae of the original α′-martensite.

They tend to thicken at first in the diffusion front and later globularize and coagulate, forming an almost compact mono-phase layer close to the surface. The thickness of this layer increased with the increasing number of thermal cycles, as Figure 4.a. shows. The same tendency was found with the increasing maximum temperature, Figure 4.b. From Figure 1. it is obvious that at the maximum temperature the stress was practically equal zero. That means that the effect of the stress on the growth of the oxygen-rich layer was rather limited.

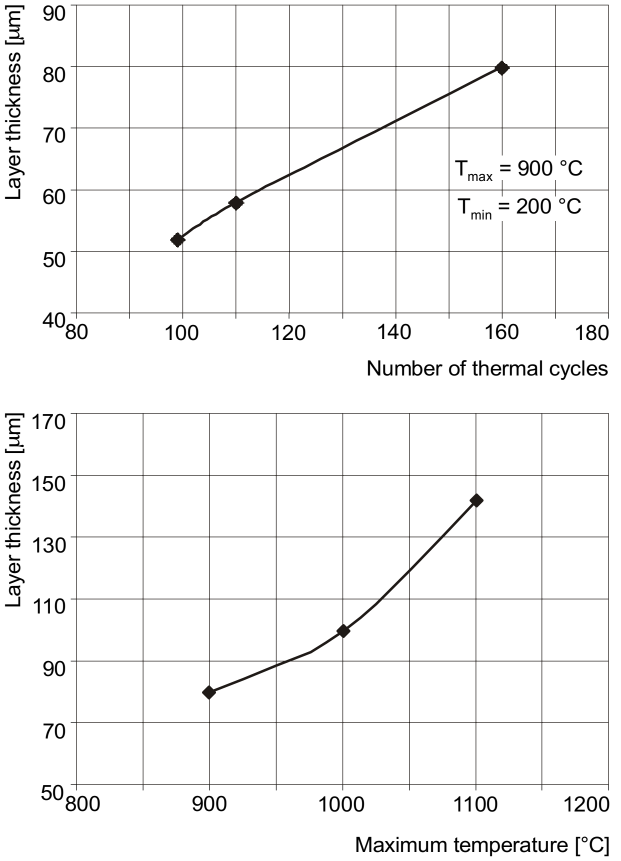

Figure 4. **a) α-stabilised layer thickness in funnction of thermal cycle number, and b) maximum temperature**

Slika 4. **a) Debljina α-stabiliziranog sloja u funkciji termičkog broja ciklusa, i b) maksimalne temperature**

The damage process

The interstitial embrittlement of the surface area due to the formation of α-stabilized layer facilitates the initiation and progress of the damage process occurring during thermal cycling. The influence of the mechanical stress may be considered in connection with surface oxide cracking and initiation of fatigue cracks. Fatigue cracks were initiated in the α-stabilized layer as is evident from Figure 3. Crossing this layer the cracks enter the area where the oxygen diffusion did not take place since the growth rate of the fatigue crack showed to be higher than the growth of the α-stabilized layer. Parallel the new surfaces of the fatigue cracks, exposed to atmospheric oxygen represent an additional entrance for the diffusion of oxygen, as it is visible on Figure 5.

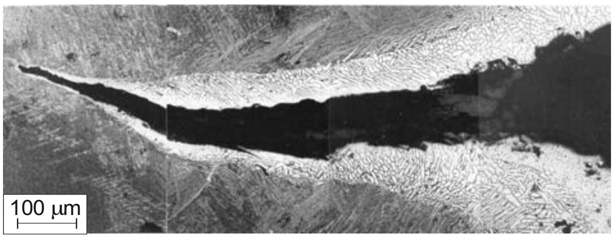

Figure 5. **α-layer on the surface of the fatigue crack**

Slika 5. **α-sloj na površini pukotine nastale zbog zamora**

The penetration of oxygen, i. e. the growth of the α-stabilized layer in these conditions can accelerate the damage process, considering embrittlement also in the vicinity to the crack tip [9]. In spite of these considerations the decisive role in the growth of the α-stabilized layer on the exposure time and temperature in our case on the number and maximum temperature of the thermal cycles, respectively.

CONCLUSIONS

Thermal cycling of the titanium alloy Ti-6Al-2.5Mo-1.5Cr at elevated temperatures resulted in the development of an α-stabilized layer, accompanied by a fatigue damage process.

Maximum temperature and total exposure time showed to be decisive for the growth of α-stabilized layer, when maximum temperature and maximum stress were in antiphase.

The oxygen-containing a phase nucleated on the lamellae of the α´-martensite when during the thermal cycling the maximum temperature exceeded the transformation temperature of the alloy.

The fatigue damage process initiated by cracking in the embrittlened α-stabilized layer propagating into the basic material, opening additional access to oxygen diffusion and α-layer formation.

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